AERONAUTICAL METEOROLOGY

By

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WITH THE COLLABORATION OF
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PREFACE

An intimate knowledge of the characteristics of the atmosphere is generally recognized as indispensable to the successful development of aeronautics. The aeronautical engineer must have at his command information regarding variations in density, pressure and temperature with height. The promoter of air lines can determine and guarantee workable schedules only if he has detailed data on wind and weather conditions along the proposed airways, particularly the frequency and strength of head and cross winds. Insurance companies cannot fix suitable premium rates without information as to the frequency of unfavorable weather conditions such as fogs, thunderstorms, excessive precipitation, etc. The pilot should know the variation in direction and velocity of winds with change in altitude; the frequency of winds of different directions and velocities at various altitudes; the principal causes of gustiness; the size and other characteristics of thunderstorms; the average height of the different types of clouds; the main characteristics of cyclones and anticyclones; and many other details of the "air and its ways." He should have a knowledge of the significance of changes in pressure, wind and cloud formation and through this knowledge be able to amplify and interpret locally the more general forecasts received for a wider territory. In fine, his grasp of the subject should be such as to enable him to derive the greatest possible advantage from every condition of wind and weather that he may meet.

The purpose of "Aeronautical Meteorology" is to supply these needs; to give in concise form the essential facts of the upper air and to point out their relation to the development and safety of aeronautics. There are in existence many excellent treatises on general meteorology, but these naturally do not

contain the detailed information most needed by the airman and on the other hand do contain much material of interest only to the professional meteorologist. In "Aeronautical Meteorology" this latter type of information has been included only so far as to provide a general groundwork for the better understanding of atmospheric processes and conditions directly related to aeronautics.

The first edition of this book appeared previous to the passage of the Air Commerce Act of 1926—before civil flying in the United States had begun to develop on a systematic basis.

Four years have elapsed since that epochal Act became effective. During this period there has been organized a nation-wide network of federally established airways. Passengers, mail and express, in ever-increasing numbers and volume, are being carried along these airways, protected by aids of various sorts, including an intensive weather reporting and forecasting service.

Consequently, much has been learned that was not known in 1926, relative to the application of meteorology to aeronautics. Also much has been added to the store of general knowledge regarding the characteristics of the atmosphere, especially those features which are found to be of special concern to air pilots.

In this second edition, effort has been made to profit from the experience and lessons of these four years to bring the book up to date in every respect. The original purpose remains unchanged, but various portions have been rewritten and rearranged with considerable new material added. Because of its outstanding importance in air transportation "Fog" forms the subject of a separate chapter instead of being combined with "Clouds," as in the first edition. The original short chapter on "Visibility" has been much expanded under the title "Ceiling and Visibility." Two entirely new chapters have been added—one on "Airship Meteorology" and the other on "Ice

Formation on Aircraft." Finally, Appendix 1 presents suggestive questions and topics for students.

The second edition differs from the first also in being the product of several authors. Mr. R. N. Covert contributed Chapter 2 on "Instruments and Methods of Observation"; Mr. V. E. Jakl, Chapter 5 on "Fog"; Mr. R. H. Weightman, Chapter 10 on "Weather Forecasting"; Lieut. F. W. Reichelderfer, U. S. N., Chapter 11 on "Airship Meteorology"; and Mr. C. G. Andrus, Chapter 13 on "Ice Formation on Aircraft." Portions of Chapter 7 on "Ceiling and Visibility" were contributed by Messrs. C. G. Andrus, H. M. Hightman, V. E. Jakl, D. M. Little, and J. A. Riley. Useful hints were received from Messrs. L. T. Samuels and R. H. Weightman in the writing of Chapters 4 and 9, respectively.

All parts of this second edition have been read critically by Dr. W. J. Humphreys; his helpful suggestions have been accepted and are gratefully acknowledged.

The author takes particular pleasure in expressing appreciation to Professor C. F. Marvin, Chief of the U. S. Weather Bureau, for his cordial and sympathetic interest throughout the preparation of this second edition as well as during the writing of the first.

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Washington, D. C.

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AERONAUTICAL METEOROLOGY

INTRODUCTION

The chief constituents of the atmosphere are nitrogen and oxygen. The other permanent gases that occur in appreciable amounts are argon, hydrogen, neon, helium, and carbon dioxide. According to Humphreys[1] the percentage distribution of these gases by volume in dry air at sea level is as follows:

Nitrogen	78.08	Neon	0.0012
Oxygen	20.94	Helium	0.0004
Argon	0.94	Carbon dioxide	0.03
Hydrogen	0.01		

Among those that occur in mere traces are krypton, xenon, ozone, ammonia, and sulphur dioxide. In addition to the above, there is always water vapor of varying amount, depending upon the season, location, temperature, and other conditions. On the average it constitutes about 1.2% of the atmosphere at the earth's surface, and the percentages of nitrogen and oxygen are then changed from those given in the table to approximately 77.08 and 20.75 respectively.

It is important to recognize that the atmosphere is a mechanical mixture, not a chemical compound. Nevertheless, its composition at the surface remains remarkably constant the world over.

There is little variation also in the lower 10 to 12 kilometers (33,000 to 40,000 ft.) of the atmosphere, owing to convective mixing.[2] At greater heights it is probable that the gases are arranged according to their molecular weights, and therefore that above 100 kilometers (60 miles) hydrogen may constitute nearly 100% of the atmosphere. Definite data on this point are lacking, however.

[1] "Physics of the Air," 2d ed.
[2] For discussion of convection see Chapter 1.

Height of the atmosphere. Observations of meteors and auroras indicate that the atmosphere extends at least to 1,000 kilometers (600 miles); how much farther is as yet purely conjectural.

The principal meteorological elements are pressure, temperature, moisture, cloudiness, precipitation, sunshine, wind direction and velocity, and visibility.

Weather is the state of these elements at a given time and place, or during a particular period and in a specified region.

Climate is the normal state of these elements for a period of years, the longer this period, the better. Means, mean maxima and minima, frequencies of certain values or conditions, etc., absolute extremes, for the hour, day, week, month, season, and year are properly included in a complete picture of the climate of a place or region.

Meteorology is the science of the earth's atmosphere, embracing therefore both weather and climate. The study of the latter, however, is separately designated **climatology.** Another branch of meteorology which has received much attention during the past thirty years is **aerology,** the study of the upper or free, air.

With the introduction of scientific methods in industry and commerce, applied meteorology has of recent years rapidly come to the front and thus we have such subdivisions as **aeronautical, marine, agricultural,** and **insurance meteorology.**

Aeronautical meteorology is that branch of meteorology which deals with the practical application of what is known of the atmosphere to the needs of aeronauts and aviators. This is the branch or subdivision upon which emphasis will be placed in this book. Most attention, moreover, will be paid to conditions in the United States, but in order to provide a suitable background for their better understanding a very brief outline of world meteorology is given in Chapter 1.

Abbreviations used in this book are as follows:

ELEMENT	UNIT	ABBREVIATION
Pressure [Barometric (P) and Vapor (e)]	Inch (mercury)	in.
	Millimeter (mercury)	mm.
	Millibar	mb.
Temperature (t)	Fahrenheit	° F.
	Centigrade	° C.
	Absolute	° A.
Relative humidity	Per cent	%
Absolute humidity	Grains per cubic foot	gr./cu. ft.
	Grams per cubic meter	g./cu. m. or g./m.^{3}
Precipitation	Inch	in.
	Millimeter	mm.
Density (ρ)[3]	Pounds per cubic foot	lb./cu. ft.
	Grams per cubic centimeter	g./c.c.
	Kilograms per cubic meter	kg./cu. m. or kg./m.^{3}
Wind velocity (v)	Miles per hour	m.p.h.
	Feet per second	ft./sec.
	Meters per second	m.p.s. or m./s.
	Kilometers per hour	km./hr.
Altitude (z or h) and distance	Foot	ft.
	Meter	m.
	Mile	mi.
	Kilometer	km.
	Mean sea level	M. S. L.

Units. In the United States, English units and the Fahrenheit temperature scale are used for surface observations, because they are the official standards for this country and are in general use by the public. For the upper air observations metric units and the centigrade temperature scale are used, in order to make the data more readily comparable with those of most other countries. Conversion tables are given in Appendix 6.

The use of different units is to be deplored, as it leads to

[3] Strictly speaking, density is the mass per unit volume, i.e., $\rho = \frac{\omega}{g}$. In common practice, however (e.g., in Smithsonian Meteorological Tables) it has been used to express weight per unit volume, and this use is adhered to in the following sections.

confusion, waste of time, and possibility of errors in converting from one to another. However, it is a condition that exists and must be endured until cured. As this book may be used by some who prefer the metric units and others who prefer the English (and similarly the centigrade and Fahrenheit temperature scales), both are used in text and tables. So far as the illustrations are concerned, many of these are taken from papers previously published in technical journals and they show the units originally used. Moreover, the purpose of illustrations is to give, not the actual values, but a general picture, and this purpose is served equally well, no matter what particular system of units is employed. As a matter of convenience, however, each legend includes the proper conversion factors.

CHAPTER 1

GENERAL CIRCULATION OF THE ATMOSPHERE

Temperature. For all practical purposes, insolation, or the sun's radiant energy, may be said to be entirely responsible for the heat of the earth's atmosphere; that from the interior of the earth and from heavenly bodies other than the sun being negligible.

The amount of insolation received by the earth as a whole varies about 7% during the year owing to the eccentricity of the earth's orbit. The time of nearest approach of earth to sun is about January 1 and that of greatest distance about July 1. Thus, the earth as a whole receives most heat during winter of the northern hemisphere and least during summer.

The earth's axis is inclined 66½° to the plane of the ecliptic and always remains parallel to itself as the earth revolves around the sun. The change thus brought about in the presentation of the earth to the sun causes an apparent migration of the latter through 47° from the Tropic of Cancer on June 21 to the Tropic of Capricorn on December 21. This migration gives rise to three important results: (1) The thermal equator, as distinguished from the geographical equator, moves northward and southward with the sun and materially affects the general planetary circulation; (2) the sun's rays fall more and more obliquely on the surface of the northern hemisphere, as the sun moves southward (and vice versa in the southern hemisphere), thus varying the amount of energy per unit of surface, not only because these rays are spread out more as their angle of incidence diminishes, but also because somewhat greater absorption occurs by reason of their longer path through the atmosphere; (3) the relative

lengths of day and night change greatly throughout the year. The following table shows the length of the longest day (hence also of the longest night) at certain latitudes:

Latitude....	0°	17°	41°	49°	63°
Duration....	12 hr.	13 hr.	15 hr.	16 hr.	20 hr.
Latitude....	66½°	67°21′	69°51′	78°11′	90°
Duration....	24 hr.	1 mo.	2 mo.	4 mo.	6 mo.

According to Abbot and Fowle, about 37% of the insolation intercepted by the earth is reflected by clouds and by the earth's surface and atmosphere. Most of the remaining 63% is transmitted by the atmosphere directly to the surface, although a small amount is absorbed by water vapor, carbon dioxide, and ozone. Much of the insolation that reaches the earth's surface is there absorbed and re-radiated as terrestrial radiation, long wave-length, which is more readily absorbed by the atmosphere than is the short wave-length solar radiation. The extent of the absorption depends upon the amount of water vapor present and therefore varies greatly from time to time in its effect at various levels. Air in contact with the earth's surface is heated or cooled by conduction. If it is heated, its density diminishes and it is forced by denser air above it, or adjacent to it, to ascend. This process is called **convection** and is one of the most important agencies in determining both the vertical and the horizontal distribution of temperature over the earth.

Land and water areas exercise another marked influence upon temperature distribution. Water surfaces reflect about 40% of the insolation reaching them. The remainder is transmitted to lower depths and absorbed, but much of it is used in evaporating the water and is therefore stored up as latent heat. The result is that water surfaces and the air in contact with them maintain a relatively constant temperature. Land areas, on the other hand, reflect and transmit very little

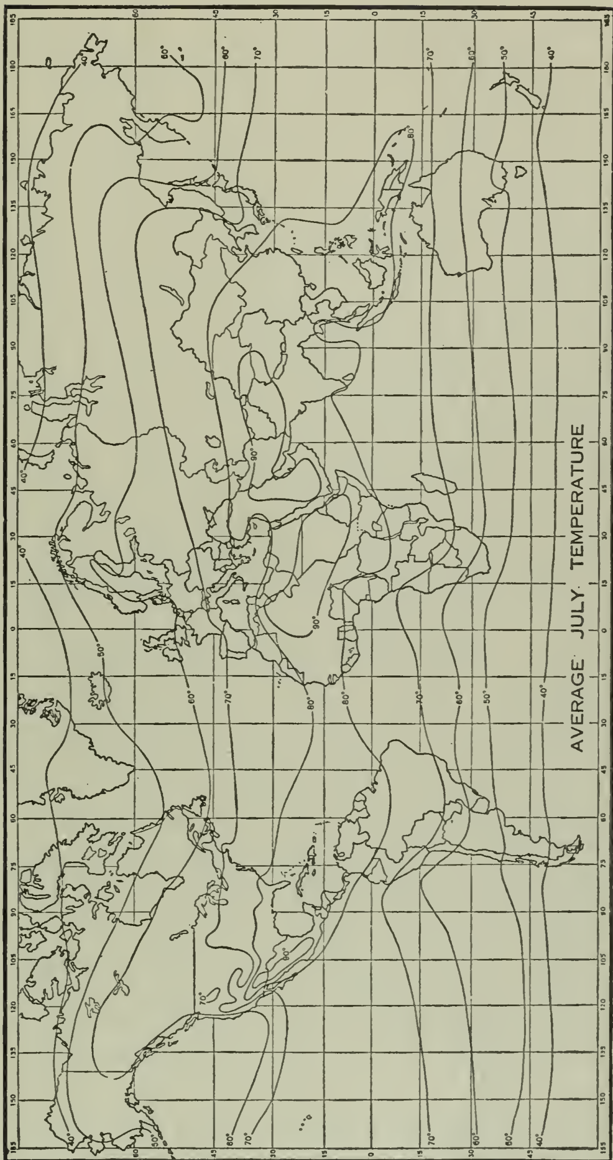

Figure 1. Average Temperatures, ° F., for the World in July
To convert °F. to °C., subtract 32 and multiply by 5/9.

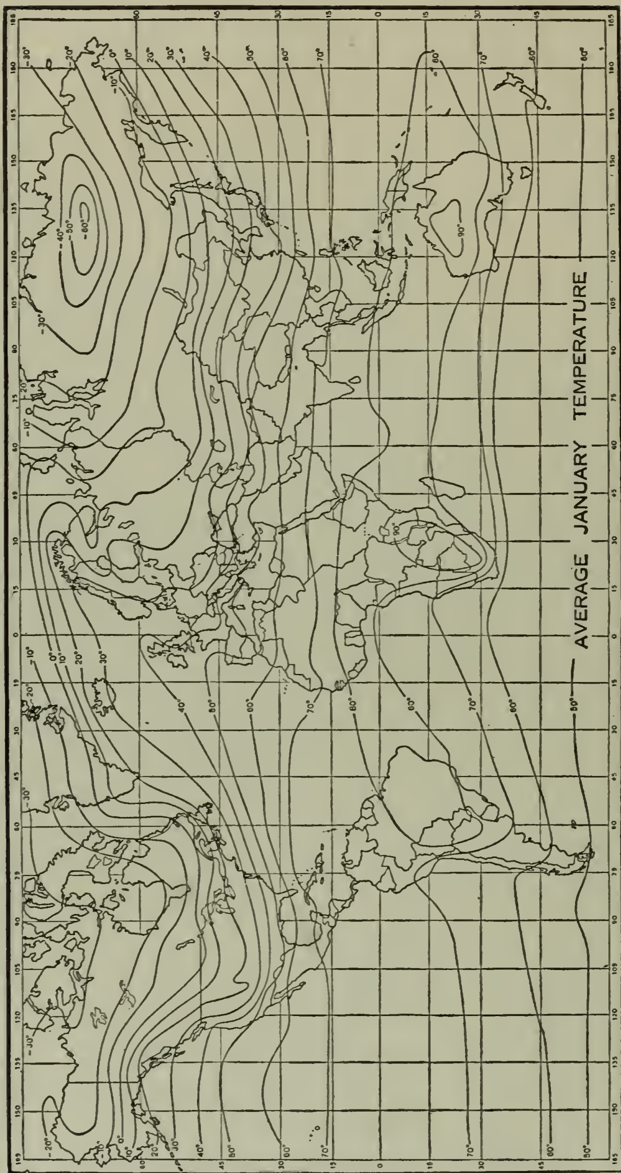

Figure 2. Average Temperatures, ° F., for the World in January
To convert °F. to °C., subtract 32 and multiply by 5/9.

insolation and there is much less evaporation. The specific heat of land is low; hence, land areas become strongly heated during insolation and similarly cooled in its absence.

The temperature distribution over the globe is in large part the result of the influences and conditions briefly outlined in the foregoing paragraphs. Isothermal charts of the world

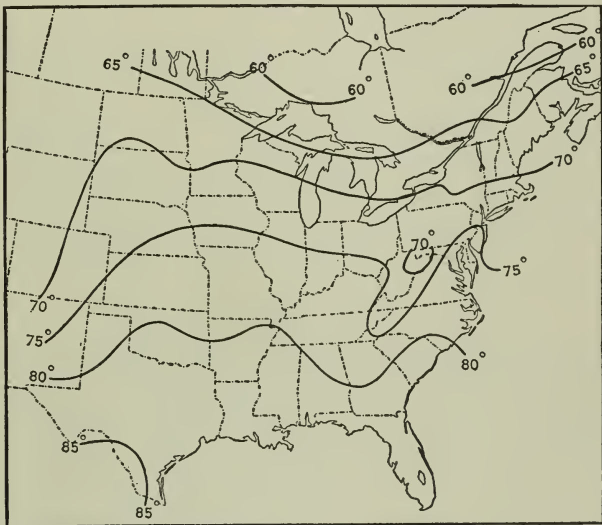

Figure 3. Average July Temperatures, ° F., in Eastern and Central United States

To convert °F. to °C., subtract 32 and multiply by 5/9.

for July and January are presented in Figures 1 and 2. The chief features are: (a) the migration of the thermal equator and the shifting of climatic zones; (b) the crowding together of isotherms in winter and the relatively large distances between them in summer; and (c) the bending of isotherms over land areas poleward in summer and equatorward in winter.

Figures 3 and 4 give in greater detail the average July and January temperatures for the United States east of the Rocky Mountains. Farther west the latitudinal change is

largely obliterated by topographic irregularities. These two months are, in most parts of the northern hemisphere, the hottest and coldest respectively; in other words, the temperature lags behind the times of greatest and least heat received from the sun. This is true because, in early summer the atmosphere is still cool from the effects of the preceding winter and in northern regions snow covers the ground until late

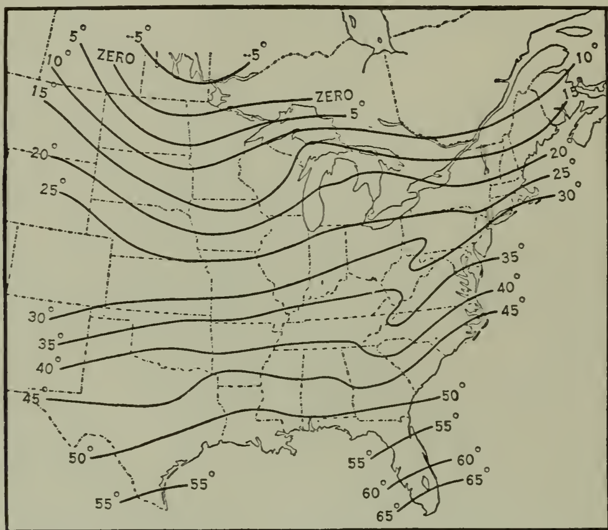

Figure 4. Average January Temperatures, ° F., in Eastern and Central United States

To convert °F. to °C., subtract 32 and multiply by 5/9.

spring. Much of the sun's heat is required to overcome these influences. When this has been accomplished, the effect of insolation increases for a time, even though the amount received is less than before. In winter the opposite of this occurs.

Similarly, there is a lag in the daily temperature march, the highest occurring, as a rule, between 2 and 4 P.M., and the lowest about the time of sunrise.

Pressure and wind. The causes of temperature distribution over the earth have been given in some detail, because of the intimate relation between temperature on the one hand and pressure and wind on the other. Changes in temperature produce changes in density which set up vertical movements resulting in changes in pressure. Horizontal air movement, or wind, represents Nature's effort to adjust these changes in pressure. Since the equatorial regions receive most heat and the polar regions least heat, one would at first suppose that pressures would be lowest in the former and gradually increase to a maximum in the latter. This is what would occur on a non-rotating earth. Because of the earth's rotation, however, the overflowing air from the tropics is deflected to the right in the northern hemisphere and to the left in the southern hemisphere by a force, d, defined in the equation

$$d = 2m\omega v \sin l,$$

in which m is the mass of the body acted upon, v its speed, l its latitude, and ω the angular velocity of the earth's rotation $\left(\frac{2\pi}{86{,}164}\right)$ (more exactly, it would require such a force to prevent deflection). The value of d is zero at the equator, but increases to $2\ m\omega v$ at the poles.

The ultimate result of the two influences, viz., decreasing temperatures from equator to poles and deflective effect of the earth's rotation, combined with the uneven distribution of land and water, is a pressure distribution which, on the average, is like that shown in Figures 5 and 6 for summer and winter respectively. These maps should be considered with Figures 76 and 77, in Chapter 12, which give the average wind conditions over the oceans. Laying aside for the moment the rather pronounced differences in pressure between summer and winter over the continents, it will be seen that there are certain broad general features common to both seasons. These features define what is customarily referred to as the "general circulation" and are discussed briefly in the following paragraphs.

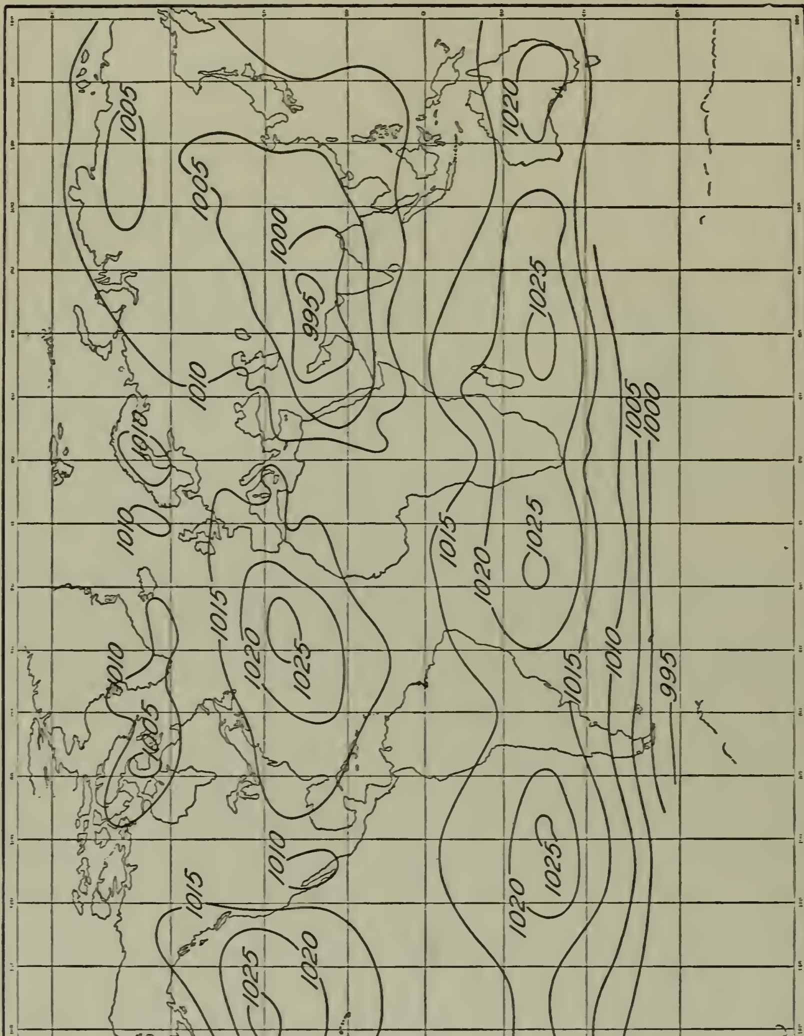

Figure 5. Average Pressure, mb., for the World in July

To convert millibars to millimeters and inches, multiply by 0.75006+ and 0.02953+, respectively.

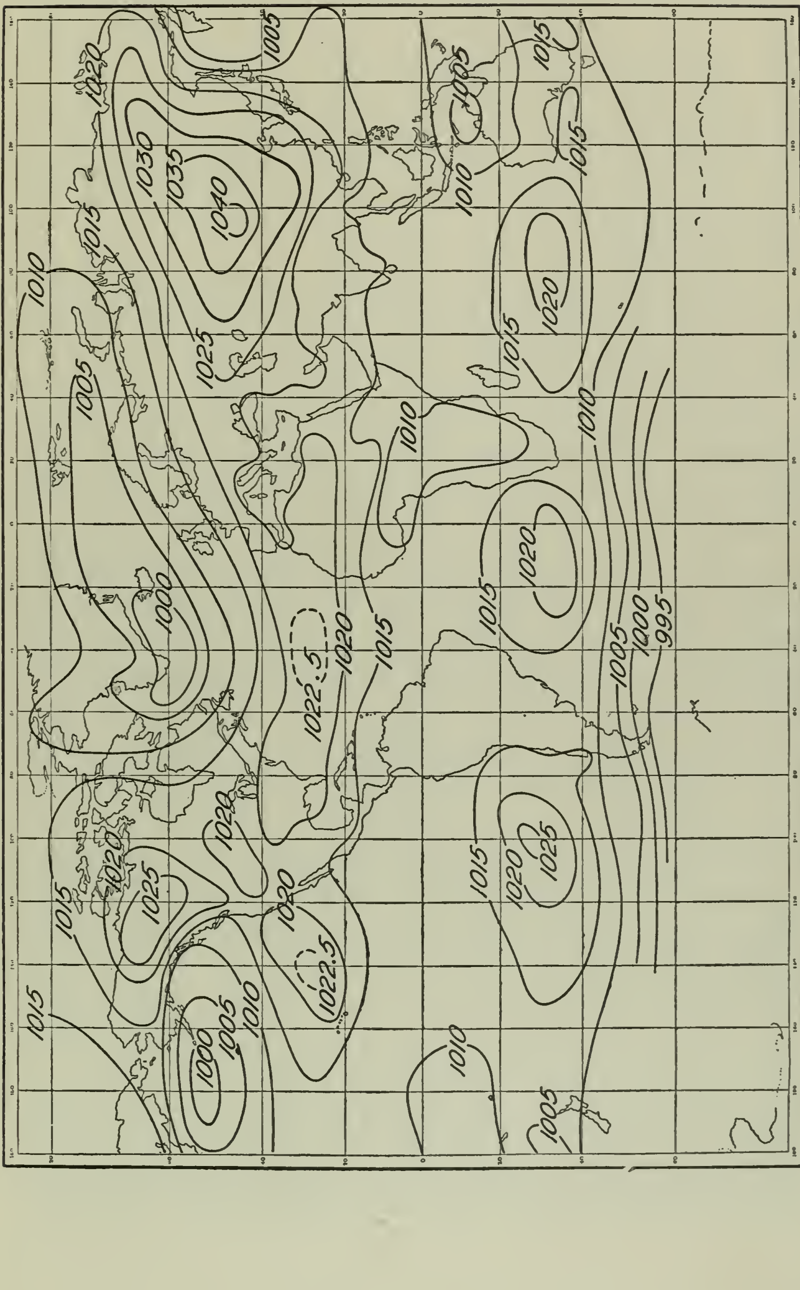

Figure 6. Average Pressure, mb., for the World in January

To convert millibars to millimeters and inches, multiply by 0.75006+ and 0.02953+, respectively.

Doldrums. A belt of low pressure in the tropics, closely following the thermal equator and characterized by light winds and calms, high temperature and high humidity, frequent rains and violent thunderstorms and squalls. The doldrums are farthest south in February, lying then close to the equator, and farthest north, latitude 10° to 15°, in August, when they provide conditions very favorable for the development of tropical cyclones.

Horse latitudes are belts of high pressure at about latitude 30° N and S, migrating with the sun and characterized by fine, clear weather and little air movement.

Pressure diminishes on either side of the horse latitudes, resulting in wind systems known as the trade winds on the equatorial side and the prevailing westerlies on the poleward side.

Trade winds, northeast in the northern hemisphere and southeast in the southern, blow fairly continuously over the oceans, especially the Atlantic, from about latitude 30° to the doldrums. According to Hann the average limits of the trade winds and the doldrums on the Atlantic are as follows:

	Summer	Winter
N. E. Trades........	35° N-11° N	26° N- 3° N
Doldrums...........	11° N- 3° N	3° N- 0°
S. E. Trades.........	3° N-25° S	0° -25° S

The east component in these winds results from the deflective effect of the earth's rotation. As they approach the doldrums, the air rises and forms a southwest wind (northwest in southern hemisphere) known as the antitrade. The depth of the trades varies considerably, but in general it is greatest during summer and least during winter, and decreases from 10 or 12 kilometers (33,000 to 40,000 ft.) near the equator to zero at about latitude 30°. Weather is generally fair, with some cloudiness but little precipitation. According to Sir Napier Shaw, the average velocities of the Atlantic trade winds are

as follows, values being given in miles per hour and meters per second:

		Jan.	Feb.	Mar.	Apr.	May	June	
N. E. Trade	m.p.h.....	10	11	11	12	11	10	
	m.p.s......	4	5	5	5	5	4	
S. E. Trade	m.p.h.....	14	13	13	12	11	12	
	m.p.s......	6	6	6	5	5	5	
		July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
N. E. Trade	m.p.h.....	9	7	8	6	8	10	9
	m.p.s......	4	3	4	3	4	4	4
S. E. Trade	m.p.h.....	12	15	17	15	16	15	14
	m.p.s......	5	7	8	7	7	7	6

The Pacific trade winds are weaker and less constant in direction; on the Indian Ocean they are lacking north of the equator in summer, during the prevalence of the southwest monsoon.

Prevailing westerlies. Poleward from the horse latitudes there is a decrease of pressure, small in amount at sea level but increasing rapidly in the upper levels. As a result of this pressure distribution, the winds throughout temperate latitudes are prevailingly from a westerly quarter. They are far from possessing the characteristics of the trade winds, however, the latter blowing almost constantly from some easterly point, although varying considerably in velocity, whereas the prevailing westerlies are frequently interrupted by passing areas of high and low pressure. They are better developed in the southern than in the northern hemisphere, in the winter than in the summer half of the year, and in the upper than in the lower levels.

As in the distribution of temperature, so in that of pressure, there are many irregularities caused by land and water areas and these irregularities greatly modify the general circulation. For example, the horse latitudes and the trade winds are best developed over the oceans, and the prevailing westerlies in the

southern hemisphere (there known as the "roaring forties") because of freedom from continental obstructions. There is also a seasonal shifting of "centers of action," i.e., more or less permanent areas of high or low pressure, between continents and oceans, purely a temperature effect, of course. The interior of Asia has the largest range, the summer average being about 1,000 millibars (29.5 in.) and the winter about 1,035 millibars (30.5 in.).

Polar conditions are not well known, but a brief summary of available information on the subject, so far as the Arctic Zone is concerned, is presented in Chapter 12.

Secondary circulations of widespread occurrence. There are certain pressure and wind formations which are not essential features of the general circulation but which are found in nearly all parts of the globe and may, therefore, quite properly be discussed here.

Monsoons. The monsoon tendency, that is, landward winds in summer and seaward in winter, exists along all coast lines, but is best developed in the southern part of Asia, owing to the large seasonal pressure range, above cited. The average depth of the winter northeast monsoon of India is about 2,000 meters (6,600 ft.), and that of the summer southwest monsoon about 5,000 meters (16,000 ft.), although there is considerable variation with latitude. The southwest monsoon is in general more pronounced than the northeast, and is intimately related to the economic life of India. Strictly speaking, however, the monsoons are not part of the *general* circulation.

In the United States the chief monsoon effects are in the eastern portion, where the prevailing winds are northwest in winter and southwest in summer; and in Texas, where they are also northwest in winter, but southeast in summer. These tendencies are well shown in Figures 7 and 8 [1] which also

[1] From "The Climates of the United States," by Robert DeC. Ward.

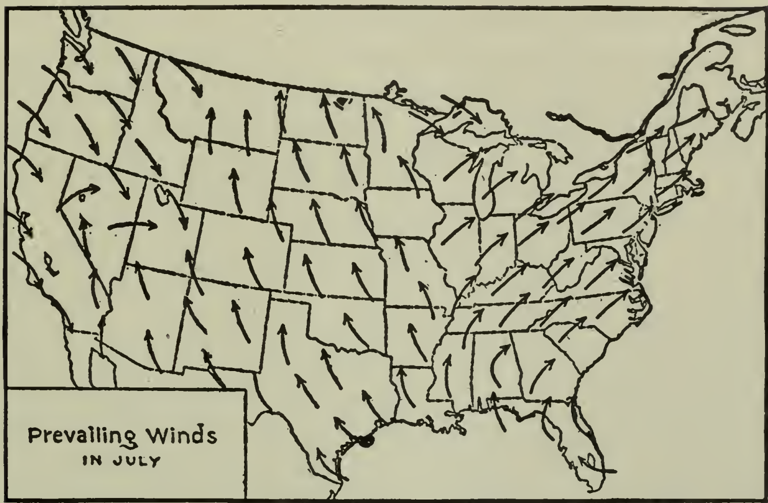

Figure 7. Prevailing Winds in the United States during July (after Ward)

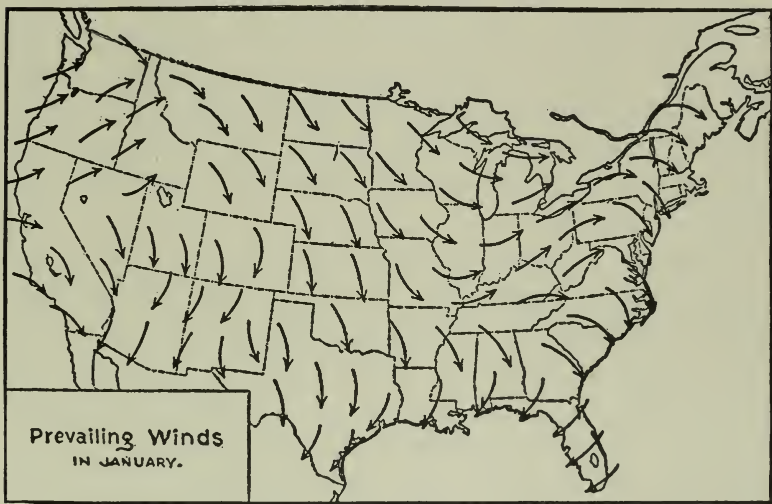

Figure 8. Prevailing Winds in the United States during January (after Ward)

indicate the broad general characteristics of the summer and winter circulation in the United States.

Land and sea breezes. On warm summer days, particularly when the pressure gradient is weak and ill-defined, a daily movement of surface winds takes place near the coast, analogous to the monsoon winds, but of far less extent. The sea breeze blows landward during the daytime, owing to the warmer and therefore less dense air over the land than over the sea. At night there is often a return wind, known as the land breeze, usually much weaker than the other. The sea breeze, when well developed, extends 10 to 25 miles (15 to 40 km.) inland, reaches a height of 1,500 feet (500 m.) or so and attains a velocity of 10 miles per hour (5 m.p.s.). The land breeze seldom extends more than 5 to 6 miles (8 to 10 km.) seaward and its height and velocity are correspondingly less than those of the sea breeze.

Mountain and valley winds. In mountainous or even ruggedly hilly country there is often, particularly at times of no general wind, a well-defined movement of air up the valleys in the daytime and an even more marked movement down the valleys at night. The latter assumes the proportions of a gale when the valley is long and fairly steep, particularly if acting as a drainage channel for a gently sloping plateau.

Chinook or foehn is a hot, dry wind blowing down a mountain slope, often raising the surface temperature 20° to 40° F. (10° to 25° C.) and evaporating large amounts of snow within a very short time. Ideal conditions are presented when a moisture laden wind is forced up and over a mountain range, in the course of which process it loses its moisture, and then as a dry wind flows down the leeward side where the temperature is low owing to active radiation or the presence of snow, or both. In flowing down the leeward

side, the air is heated adiabatically which rapid rate makes still greater the contrast with the previously cooled surface air. This wind is best developed in the Swiss Alps where it is known as the "foehn" and on the eastern slope of the Rocky Mountains, particularly in Montana and Wyoming, where it is famous as the "chinook."

CHAPTER 2

INSTRUMENTS AND METHODS OF OBSERVATION

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Observations are of two kinds—instrumental and non-instrumental. Instruments also are of two kinds—direct, or eye-reading, and automatic or recording. Such phenomena as the state of the weather, visibility, the kind and amount of clouds, the beginning, ending, intensity, and location of thunderstorms, tornadoes, etc., are observed without the aid of instruments. Observations of pressure, temperature, humidity, speed of cloud movement, wind velocity, duration of sunshine, and intensity of solar radiation are made by means of instruments. Direction of cloud movement and wind direction are observed by both methods.

Beaufort scale of wind force. In some cases, particularly at sea, wind velocity or force is estimated non-instrumentally in accordance with the scale proposed by Admiral Beaufort in 1805. It was based upon the effects produced by various wind speeds on water craft, but it was later adapted for use on land also. Although lacking the precision of instrumental methods, with practice the use of this scale leads to fairly accurate estimates and has provided very valuable information regarding winds at sea. The scale consists of 13 groups, 0 to 12 inclusive, and the designation or specification and the equivalent limiting wind speeds of these groups as adopted in the United States and Great Britain are given in the tabulation on page 23.

Beaufort Scale of Wind Force

Beaufort Number	Explanatory Titles	Mode of Estimating Aboard Sailing Vessels	Specifications for Use on Land	Miles per Hour (statute)	Meters per Second	Terms used in U.S. Weather Bureau Forecasts
0	Calm		Calm, smoke rises vertically.	Less than 1	Less than 0.3	
1	Light air	Sufficient wind for working ship	Direction of wind shown by smoke drift, but not by wind vanes.	1–3	0.3– 1.5	Light
2	Slight breeze		Wind felt on face; leaves rustle; ordinary vane moved by wind.	4–7	1.6– 3.3	
3	Gentle breeze		Leaves and small twigs in constant motion; wind extends light flag.	8–12	3.4– 5.4	Gentle
4	Mod. breeze	Forces most advantageous for sailing with leading wind and all sail drawing	Raises dust and loose paper; small branches are moved.	13–18	5.5– 7.9	Moderate
5	Fresh breeze		Small trees in leaf begin to sway; crested wavelets form on inland waters.	19–24	8.0–10.7	Fresh
6	Strong breeze	Reduction of sail necessary with leading wind	Large branches in motion; whistling heard in telegraph wires; umbrellas used with difficulty.	25–31	10.8–13.8	Strong
7	High wind		Whole trees in motion; inconvenience felt in walking against wind.	32–38	13.9–17.1	
8	Gale	Considerable reduction of sail necessary even with wind quartering	Breaks twigs off trees; generally impedes progress.	39–46	17.2–20.7	Gale
9	Strong gale		Slight structural damage occurs (chimney pots and slate removed).	47–54	20.8–24.4	
10	Whole gale	Close reefed sail running, or hove to under storm sail	Seldom experienced inland; trees uprooted; considerable structural damage occurs.	55–63	24.5–28.4	Whole gale
11	Storm		Very rarely experienced; accompanied by widespread damage.	64–75	28.5–33.5	
12	Hurricane	No sail can stand even when running	....	Above 75	33.6 or above	Hurricane

Instrumental Equipment Used in Airways Service

The general character of weather service required for the safe and efficient operation of airways activities is presented in Chapter 14. As stated in that chapter, there are two chief classes of stations: (1) at the more important terminal airports; and (2) at suitably located points on the airways. Many of the latter are at or very close to intermediate landing fields provided by the Department of Commerce or by local interests. The instrumental equipment required, as shown by experience, for these two types of stations is given in the following paragraphs. Many other instruments that are standard in general meteorological work, such as maximum and minimum thermometers, rain gage, sunshine recorder, etc., are not included here, since they are not used in the airways service. Information concerning them is available in circulars that can be obtained from the U. S. Weather Bureau, Washington, D. C.; also in works on general meteorology.

Airport stations. The standard equipment at an airport station usually consists of the following:

Thermometer shelter, large-sized, mounted on 5-foot (1.5 m.) steel support, with whirling apparatus for wet and dry-bulb psychrometer installed within; telethermoscope; mercurial and aneroid barometers; barograph; 3-cup 1/60-mile anemometer with wind-direction and velocity indicator; 18-foot (5.5 m.) wind-instrument support with anemometer crossarm; 4-foot (1.2 m.) metal wind vane and wind-vane contacts; ceiling-light projector and alidade or other ceiling height indicator; and pilot-balloon equipment.

Some variations from the foregoing are found: Steel towers up to 50 feet (15 m.) in height are sometimes needed for the exposure of wind instruments. A smaller shelter (cotton-region type) mounted on a wooden support is sometimes employed instead of the large one, a sling psychrometer supplanting the whirled wet and dry-bulb psychrometer. The

equipment is occasionally expanded by the addition of a hygrograph or a hygrothermograph.

Intermediate airways stations. The standard equipment at an intermediate station consists of the following:

Thermometer shelter with exposed thermometer; aneroid barometer; 3-cup, 1/60-mile anemometer with velocity indicator; anemometer support for airways tower at Department of Commerce station; or a 12-foot (3.5 m.) wind-instrument support with 3-foot (1 m.) metal wind vane where a tower is not available.

The foregoing is occasionally supplemented by a contacting wind vane, accompanied by a wind-direction and velocity indicator, instead of the velocity indicator. A large number of these stations are equipped with ceiling-light projectors and alidades. Small rubber balloons are used to a considerable extent for daytime observations of ceiling.

Temperature-Measuring Instruments

Shelters. Thermometers and other temperature-measuring and recording instruments, such as telethermoscopes, thermographs, and hygrothermographs, require free exposure to the outdoor air, and at the same time must be shielded from the direct or reflected rays of the sun and be free from the effects of artificial heat. This is accomplished by placing such instruments in a specially constructed shelter of the type shown in Plate I. These are box-like screens of wood having a double roof, sides of open, louvered or double-board construction, and a floor with only enough openings to permit of some air circulation and to dispose of the rain or snow which may occasionally be driven in by high winds. The sides allow a reasonably free movement of the air through the shelter when there is wind, so that the temperature of the air within the shelter is sensibly the same as that without at the same elevation. To secure the greatest degree of reflection from direct insolation, shelters are painted a pure white.

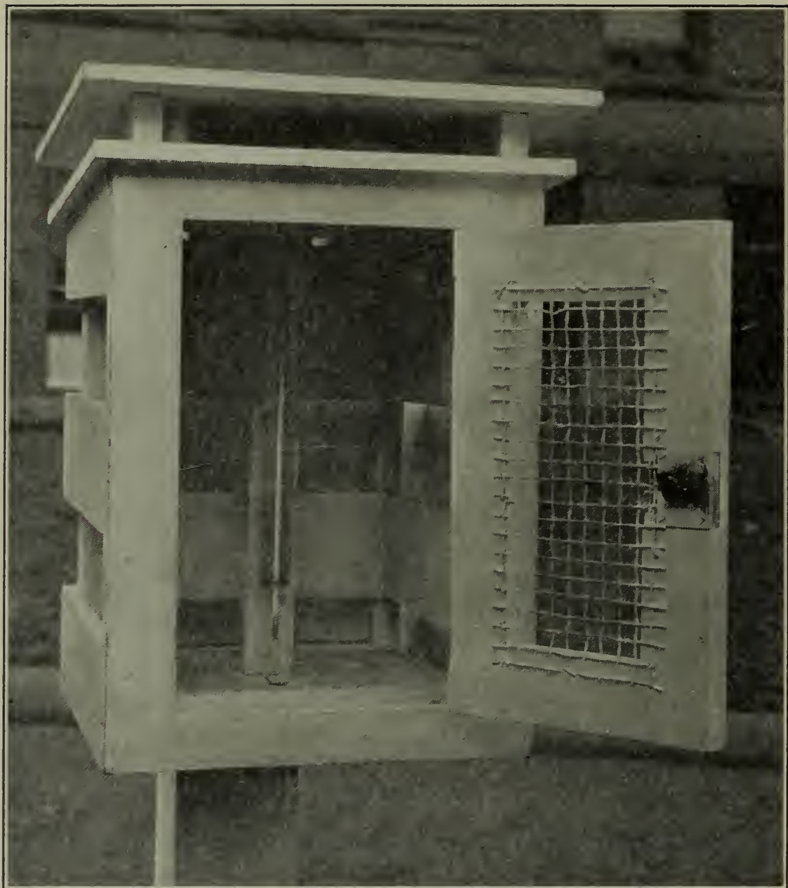


Plate I. Exposed Thermometer in Airways Shelter

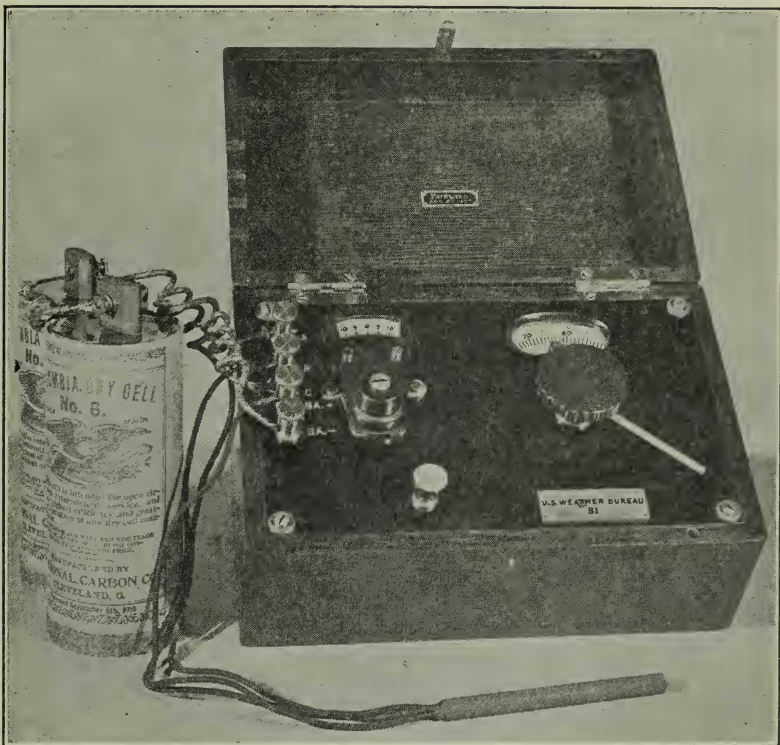


Plate II. Telethermoscope

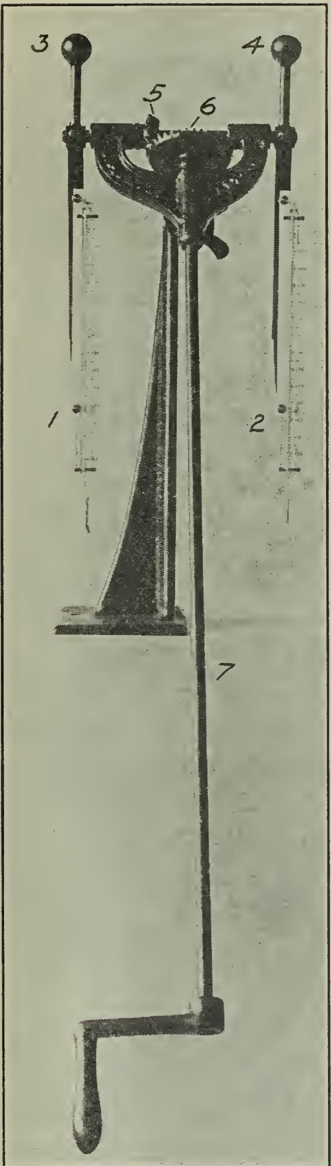
Thermometers used in airways service in the United States are Fahrenheit, stem-graduated, mercury-in-glass instruments attached to aluminum backs. One of these so-called exposed thermometers mounted in an airways shelter is shown in Plate I. Their freezing points are found as usual by immersing the bulbs and most of the column of mercury in pure melting ice. The accuracy of the balance of the scale is determined by placing the thermometer in a temperature-controlled water or alcohol bath for temperatures above and below the freezing point respectively, the points of the scale being fixed by comparison with the readings of a substandard thermometer, also immersed in the same bath. Corrections are determined for each ten degrees of scale above and below the freezing point.

Telethermoscopes, illustrated in Plate II, are electrical resistance thermometers employed for measuring the temperature of the free air in the shelter by reading an indicator which is located in the office indoors. The shelter houses a bulb which consists of a coil of nearly pure nickel wire, having a resistance of about 100 ohms at ordinary temperatures, sealed with paraffin into a nickel-plated brass tube. The coil is connected through a three-wire circuit with the indicator by means of which the changes of resistance may be measured and the corresponding temperatures indicated on a scale.

Humidity-Measuring Instruments

Observations at airport and airways stations include readings of the wet and dry-bulb psychrometer to give the temperature of the dew-point by reference to suitable tables. The dew-point temperature is found useful in connection with the forecasting of fog. Two types of the whirled or ventilated wet and dry-bulb psychrometer are employed, as follows:

(a) Whirling apparatus for psychrometer. This device is shown in Plate III. Two accurate stem-graduated mer-



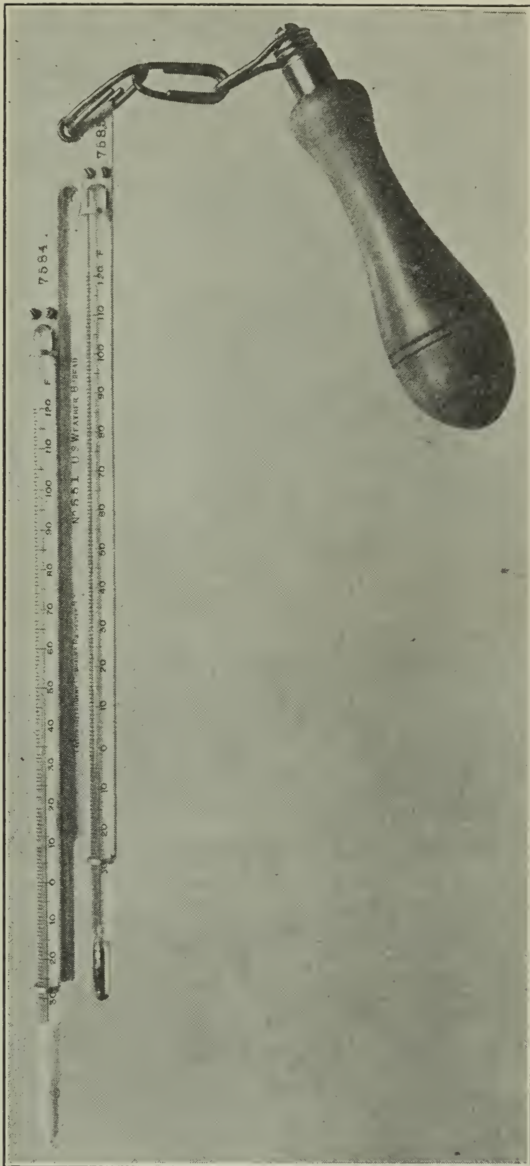


Plate III. (*Left*) Whirling Apparatus for Wet and Dry Bulb Psychrometer
Plate IV. (*Right*) Sling Psychrometer

curial thermometers (1) and (2) of the kind described above are mounted on supports attached to counterbalanced iron arms (3) and (4), the hubs of which are pinned to a spindle carrying a cast-iron pinion (5). As readily seen, the whirling of the thermometers is accomplished by turning the bevel gear (6) and attached crankshaft (7). In practice the whirling apparatus is securely screwed to the floor of a large instrument shelter with the crankshaft projecting through the front of the shelter. The wet bulb and a short length of the stem are covered with fine, loosely woven muslin carefully washed to remove the sizing. Pure, clean water is used for wetting, and the muslin removed whenever it becomes at all dirty; otherwise the readings would be rendered incorrect.

(b) Psychrometer for hand whirling, or the sling psychrometer, is mainly used in field work when the whirling apparatus is not available, or is omitted to make unnecessary the use of a costly shelter. As shown in Plate IV, the two thermometers, similar to those used with the whirling apparatus, are mounted parallel and near together on an aluminum back. By means of the handle and attached linkage, the thermometers may be whirled at the desired rate. To obtain thoroughly accurate readings, the instrument should be whirled in the shade, and the observer face the wind so as to avoid temperature effects due to the heat of the body.

When either type of psychrometer is used, the single exposed thermometer may be dispensed with.

Hygrothermographs and hair hygrographs. The first, as the name indicates, a combination of the thermograph and hygrograph, is shown in Plate V; the second, for relative humidity records alone, in Plate VI. Both of the instruments, so far as the hygrographs are concerned, are a development of the hair hygrometer. The expansion and contraction of a bundle of human hair, resulting from the absorption or

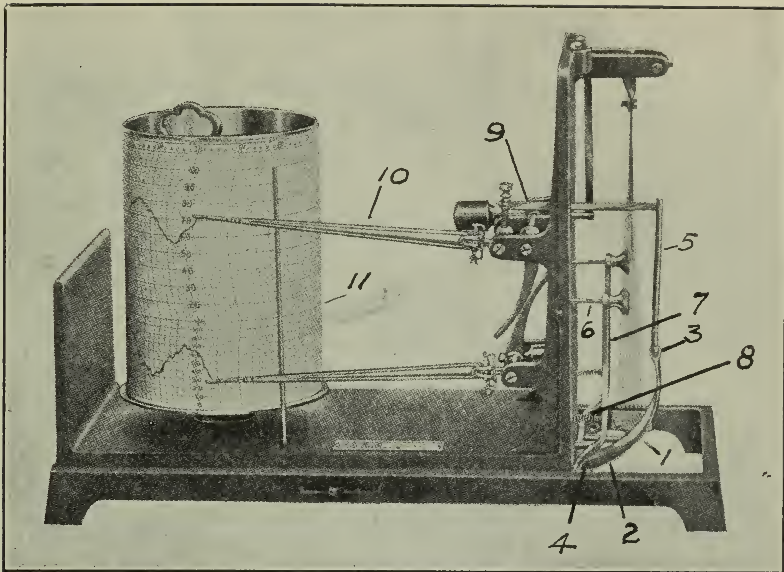


Plate V. Hygrothermograph

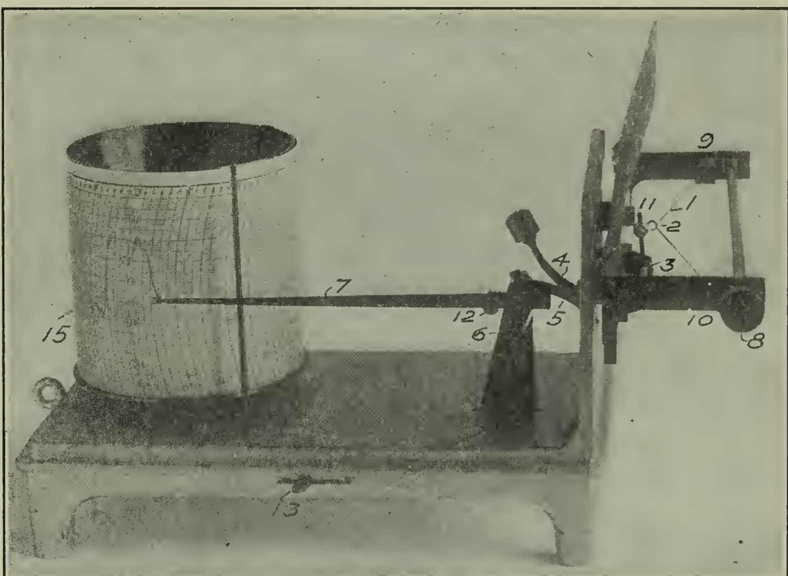


Plate VI. Hygrograph

loss of atmospheric moisture, cause the motion of a pen across a record sheet having a scale of equal parts ranging from 0% to 100% relative humidity. All oily substance must have been removed from the hair; also for continued accuracy the hair and linkage must be kept free of dirt.

Referring to Plate VI, the lengthening and shortening of the bundle of hairs (1), passed through the hook on lever arm (2), moves the latter to the left or right respectively, producing rotation of the spindle (3). This in turn moves the lever arm (4) counterweighted at its outer end and so shaped with respect to piece (5) attached to the pen-arm axis carried by post (6) as to produce motion of the pen-arm (7) over the relative humidity chart.

Adjustment of the pen on the record sheet to the current relative humidity, as found from a reading of the wet and dry-bulb psychrometer, is made at (8); the turning of the thumbscrew thus increasing or decreasing the distance between the hair supports (9) and (10). Range adjustment is provided at (11), and the pressure of the pen on the record sheet at (12). The pen is entirely removed from contact with the sheet by the bell-crank lever (13) which moves the upright bar (14). Record cylinder (15) is rotated by an 8-day clock; a 7-day record being secured.

In the hygrothermograph illustrated by Plate V, the hygrograph portion does not differ in principle from that shown in Plate VI, but the bundle of hairs is placed vertically instead of horizontally, the pen writing its record near the bottom of the sheet on the cylinder, while the upper pen shows the free-air temperature. Referring to Plate V, the actuating temperature element (1) is a bourdon tube, elliptical in cross-section with walls of thin phosphor-bronze either gold or silver plated and polished. The tube is bent into an arc of nearly 2-inch radius. It is carefully soldered to a triangular-shaped bar at (2), and to the header (3), where a short piece of lead tubing is placed, through which pure grain alco-

hol is introduced, and the tube then sealed off under pressure. The triangular bar is pivoted at (4), while the header carries a rod (5) connected to the linkage (9) actuating the pen-arm. Screw (6) is operated to adjust the pen to the current temperature by turning the pivoted end of the bulb by means of the attached arm (7), held in place by the spring (8). The linkage also permits of the adjustment of the range. The pen-arm (10) is made of thin spring brass or aluminum. The cylinder (11) is driven by an 8-day clock within.

A rising temperature causes the alcohol in the bulb to expand, resulting in an outward pressure of the alcohol which in turn reduces the curvature of the bulb and moves the linkage bar upward with a corresponding rise of the pen on the record sheet. Records are corrected to agree with the observations of the exposed thermometer or that of the dry bulb of the psychrometer, and the exact time of the observation is marked on the record by displacing the linkage rod slightly, thus causing the pen to trace a short vertical line.

Pressure-Measuring Instruments

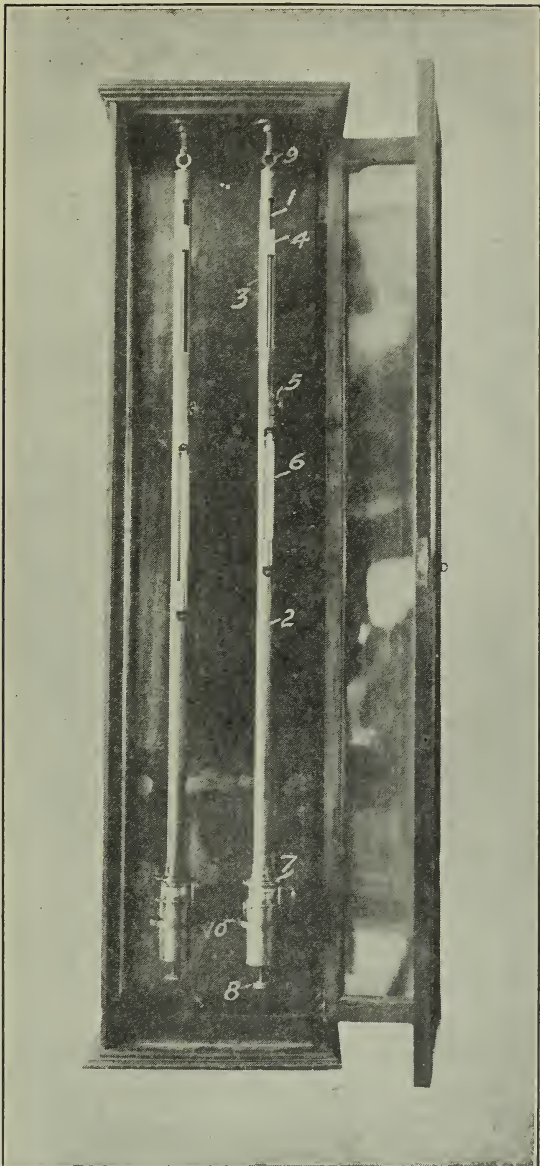
The frequent observations of atmospheric pressure made at airport and airways stations serve two purposes: As a basis, when supplemented by similar observations from stations in the three-hourly network, for short-range forecasts, for weather along the airway, issued from designated Weather Bureau airport stations; and to enable pilots to make allowances for changes in pressure in connection with altimeter readings.

Airways stations are equipped with good-quality aneroids; airport stations in addition have one and sometimes two mercurial barometers, and an aneroid barograph. The readings from the more accurate mercurial barometers provide a check on those made with aneroids and barographs. Each of the

first-order Weather Bureau stations is also equipped with mercurial barometers and a barograph.

Mercurial barometers are shown in Plate VII. Before sending to a station, the instrument is carefully compared with a sub-standard barometer for determination of the instrumental correction. Thereafter its accuracy is assured by frequent comparative readings of the station and extra barometers, or, if only one instrument is in service at the airport station, by a comparison with the mercurial barometer at a nearby first-order Weather Bureau office. Lack of progressive changes between the readings of the compared barometers, made at intervals of one to three months, indicates as a rule their continued good condition.

Referring to Plate VII: (1) is a glass tube having an inside diameter of nearly ¼ inch (6 mm.). This is inclosed in a thin brass tube (2), having large openings on opposite sides near the top through which the height of the mercury in the tube within can be measured on the scale (3), and by the vernier (4) to the nearest thousandth of an inch. The vernier (4) is attached to a second tube free to slide within tube (2), the motion being produced by rack and pinion, the knurled head of the latter being seen at (5). The attached thermometer (6) has its bulb placed between the metal case and the barometer tube proper, so as to indicate approximately the mean temperature of case and mercury. The cistern (7) is of the Fortin type, the special feature being the manner of adjustment of the mercury to the fixed ivory point forming the zero of the scale. The raising and lowering of the mercury is accomplished by means of the screw (8), the inner or upper end of which acts on the kid-leather bag forming the bottom of the cistern proper. Details of the cistern are shown in Plate VIII. Air passes into it through the flexible leather joint between the upper boxwood portion and the glass tube. The brass ring (9), Plate VII, engages a hook whereby the instrument is suspended from the top of the box often



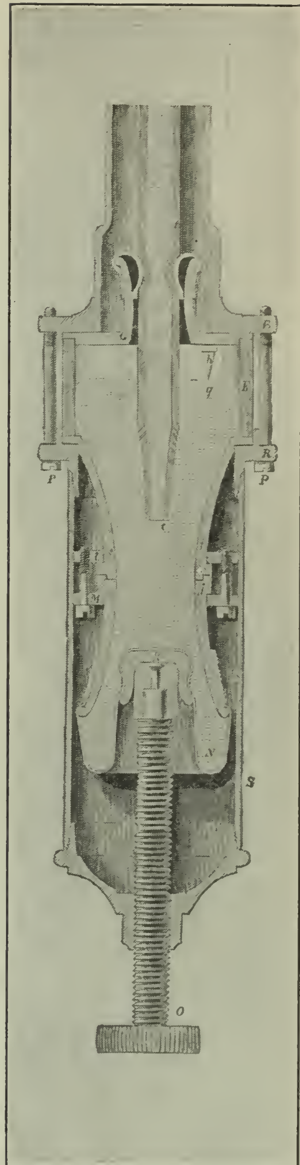


Plate VII. (*Left*) Mercury Barometer (Fortin Cistern) in Box
Plate VIII. (*Right*) Details of Barometer Cistern

used to house the barometer. Verticality of the barometer is secured by allowing it to come to rest under gravity when suspended from the hook, and then clamping the cistern end by means of the three screws in ring (10) attached to the back of the box.

Instead of using a box, a single barometer is frequently mounted on a board. As a general rule for installation, either mercurial or aneroid barometers should be located where they will not be subject to undue jarring, to extremes of heat or cold and rapid changes of temperature. They should be placed where the sun will not shine on them, but at the same time be well lighted, for both night and day observations.

Aneroid barometers. The instruments illustrated in Plates IX and X are widely used in airways service, and are particularly useful in measuring pressure changes. They are rugged and well made; when kept in adjustment they can be depended on to give readings of pressure to within 0.04 or 0.05 inch (about 1 mm.). This aneroid, in common with nearly all others, utilizes the expansion, with decrease of air pressure, and contraction, with increase of air pressure, of a corrugated shell whose ends are kept apart by an internal spring as the balancing pressure element. The air pressure is indicated by a hand moved over a dial by a suitable linkage, including a small flexible chain. Aneroids are scaled for other ranges of pressure than that shown, to make possible their use at different elevations; e.g., 24 to 31 inches, and 20 to 31 inches, etc. The dial is 5½ inches (140 mm.) in diameter, the case made of brass, and the 26 to 31-inch scale graduated to 0.02-inch subdivisions.[1]

Plate X shows the mechanism in detail. (1) is the corrugated aneroid shell made of thin German silver, the diameter 2-13/16 inches (about 70 mm.) and the thickness about ¼ inch (6 mm.) at the periphery. Steel spring (2), coupled

[1] Aneroids used in the airways service in the United States are all scaled in inches; those in countries having the metric system are graduated to read in millimeters or in half millimeters.

Plate IX. Aneroid Barometer

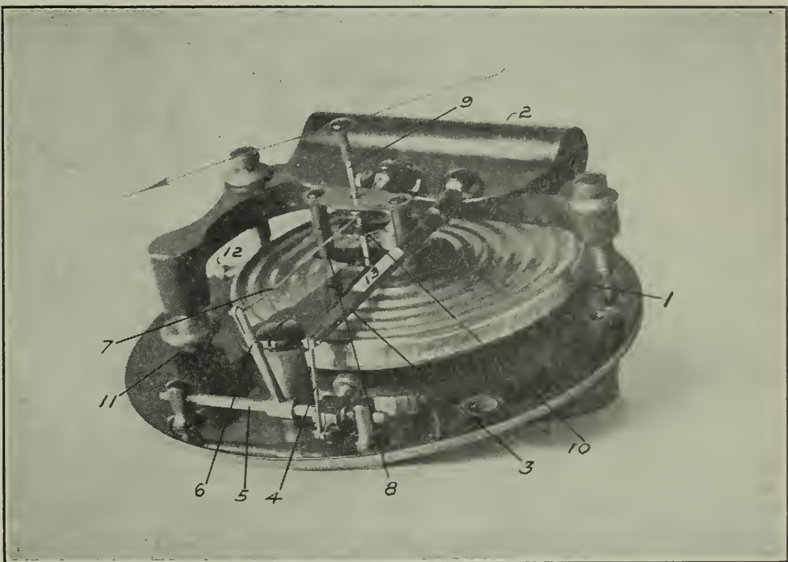


Plate X. Case of Aneroid Barometer Removed to Show Details of Mechanism

by a knife edge to the stud on the shell, balances the air pressure tending to collapse the shell. Variations of air pressure cause corresponding movements of the shell along its vertical axis, and the upper side of the D spring with the attached compound bar (3) moves with it. Link (4) changes the linear motion of (3) to the rotary motion of the pivoted spindle (5). Lever arm (6) rotates with the spindle and at its outer end is a loose link (7) joined to the fine brass chain (8). This latter produces in turn the rotation of the axis (9), the chain attached to and passing around a small arbor firmly secured to the axis. (10) is a light helical spring which keeps the chain and linkage taut. Adjustment of the pressure to agree with a mercurial barometer is accomplished at (11), a screw reached through the back of the case and the mounting plate operating to move spring (2) and its support. The vacuum shell is exhausted through the tube at (12) which is closed by pinching and sealing with solder. At (13) is a piece of steel about ½ inch (13 mm.) long and 1/32 x ⅛ inch (about 1 x 3 mm.) in section brazed to the brass of bar (3). This bimetallic arrangement provides compensation for the instrument over a considerable range of temperature, the flexure of the bar being such as nearly to offset the temperature effect on the spring and shell and connected linkage.

Aneroid barograph. Barographs of the type shown in Plate XI are used to obtain records of atmospheric pressure, but, as with all secondary instruments, their continued accuracy is assured only by frequent comparisons with the mercurial barometer. They are placed indoors where convenient to read, and as a rule should be protected from temperature changes, etc., in the same manner as are aneroid barometers.

Referring to Plate XI, the pressure element (1) is a corrugated tube of thin brass, with a stiff spring within, which prevents the element from collapsing under atmospheric pressure when the element has been exhausted of air. It is adjustably attached to the base plate (2). The stem (3) at-

tached to the upper end of the sylphon pressure element moves up and down with changes of pressure, its motion being transmitted to the recording pen (4) through the pivoted lever (5), link (6), and bell crank (7) attached to pivoted spindle (8) to which the pen-arm is also rigidly fixed. Adjustment

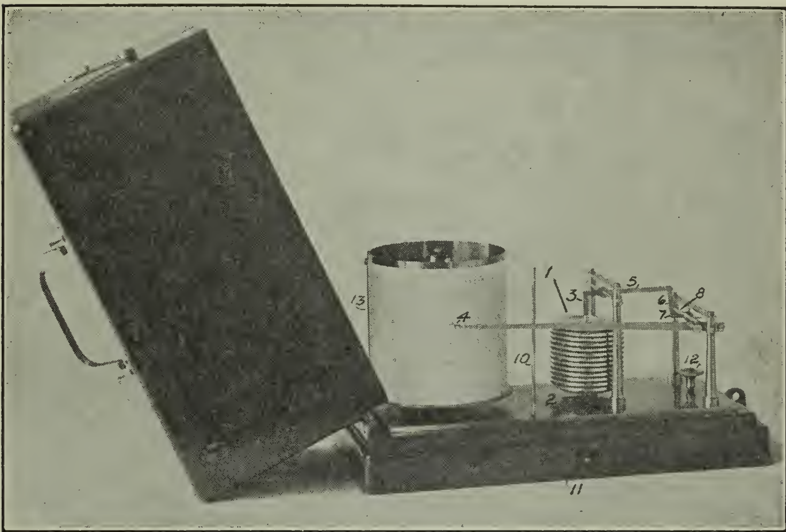


Plate XI. Barograph

of the pen pressure on the record sheet is made by means of bar (10) moved by lever (11) projecting through the case. The turning of the milled-head thumbscrew (12) on the top of the base plate near the right hand gives the adjustment of the pen to the current pressure to agree with readings of the mercurial barometer. The thumbscrew operates to turn a pivoted lever arm, resulting in the slight raising or lowering of the entire sylphon. Record cylinder (13) is driven by an eight-day clock within, and the seven-day records secured are corrected for pressure and time to agree with the observations of the mercurial barometer.

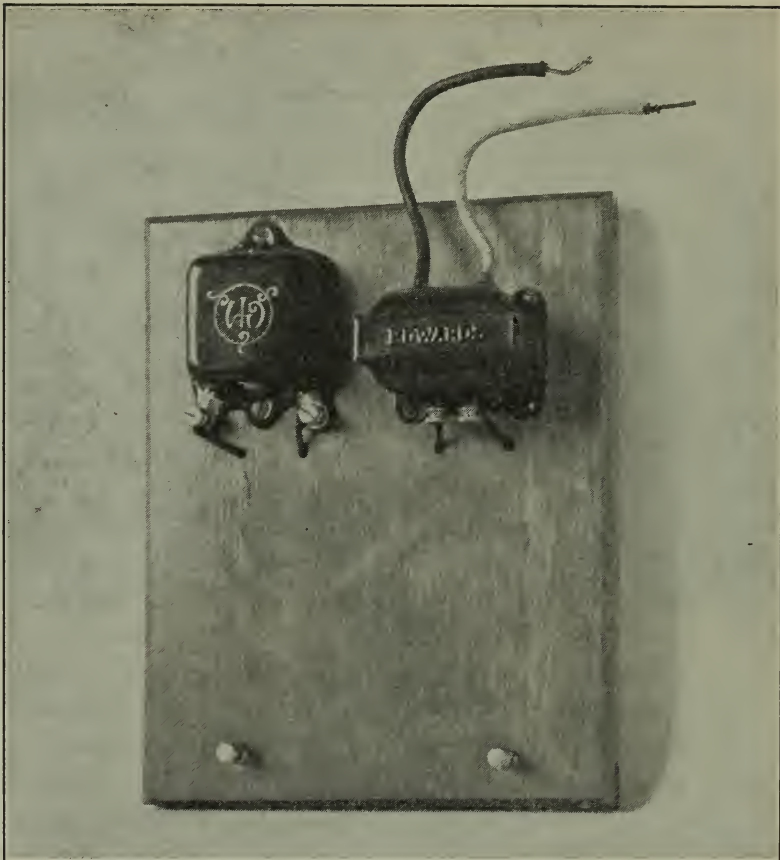


Plate XII. Wind Velocity Indicator, Transformer Type

Wind-Measuring Instruments

The intensive weather-reporting service at airport and airways stations has led to practically the exclusive use of instruments for *indicating* the wind direction and velocity; velocity by means of a 1/60-mile anemometer and an electrically operated buzzer, Plate XII; direction by means of a wind vane and contacting device electrically connected with four incandescent lamps mounted so as to correspond to the four points of the compass, Plate XIII.

Exposure. Wind instruments are exposed where a free movement of the wind occurs, obstructed as little as possible by nearby structures or objects. This is obtained by elevating the vane or anemometer by means of vertical pipe supports, usually mounted on buildings, but sometimes on steel towers. Both instruments and supports must be readily accessible for cleaning, oiling, adjustment, and other needed attention. Indicators are placed indoors where convenient for observation and electrical connection.

Anemometers. The type of anemometer used is illustrated by Plate XIV. It consists of three 5-inch (125 mm.) hemispherical cups mounted on transverse arms of steel tubing attached to a vertical spindle. The system is rotated by the wind, and suitable gearing provided for registering the wind movement, with electrical contacts for closing a circuit as many times per minute as the wind is blowing miles per hour.

Referring to Plate XIV: The cup-wheel (1) is made of hemispherical cups of aluminum or occasionally of copper for use where aluminum is subject to rapid corrosion; the cups mounted on arms 6.29 inches (160 mm.) from the axis of rotation. The wheel is attached by set screw (2) to a steel spindle within the casing having a plain bearing at the upper end and a step bearing at the bottom. A steel worm wheel on the spindle transmits motion to the wheel (3), on the axis of which is a second worm meshing with the pinion (4)

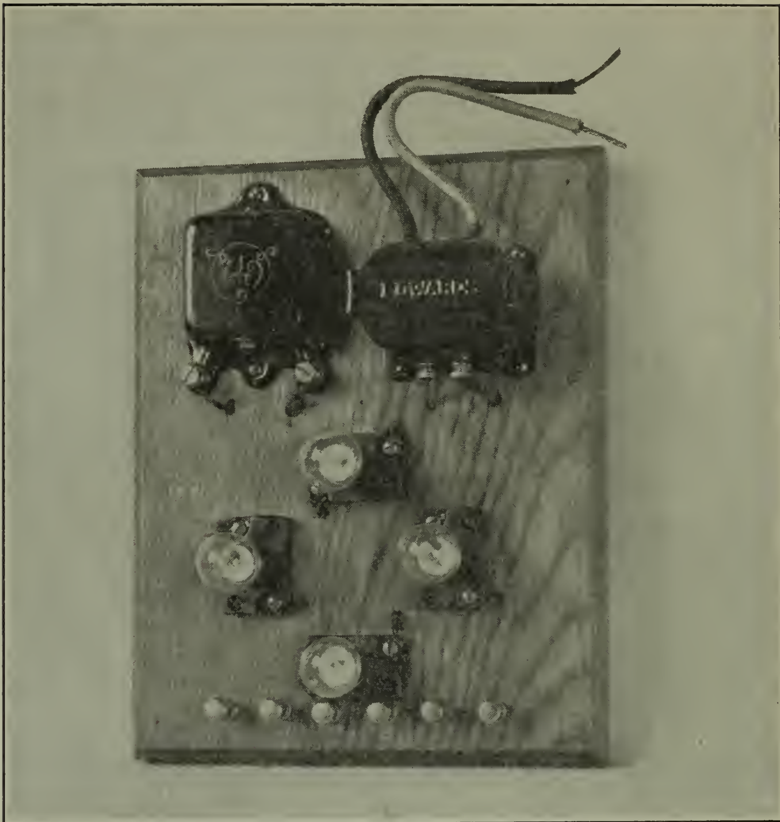


Plate XIII. Wind Direction and Velocity Indicator

which turns the two dial wheels (5), the outer one of which has 100 teeth and the inner 99, so that for each revolution of the former, the inner wheel moves one graduation, equivalent to an indicated wind movement of 10 miles. The inner dial, therefore, gives the reading to tens of miles as referred

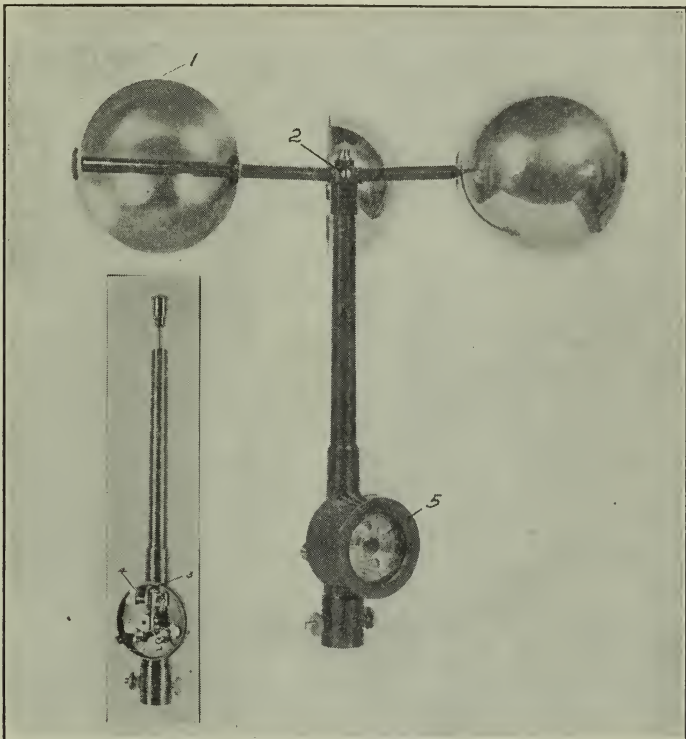


Plate XIV. Three-Cup Anemometer Complete with Cups

to the zero of the outer dial and the latter gives the additional miles and tenths by reference to an index. Electrical indication is secured by the closure of a circuit which includes a buzzer in the distant office, current being provided by either dry cells or an alternating-current transformer.

Anemometers like those illustrated are made to register kilometers instead of miles by a suitable alteration of the gear-

ing, the graduation of the dials, however, being the same for each type of instrument.

Dines pressure-tube anemometer. Instruments of this type are used primarily to obtain a knowledge of the gustiness of the wind. The records are usually in the form of a band resulting from the successive gusts or lulls, and a median line

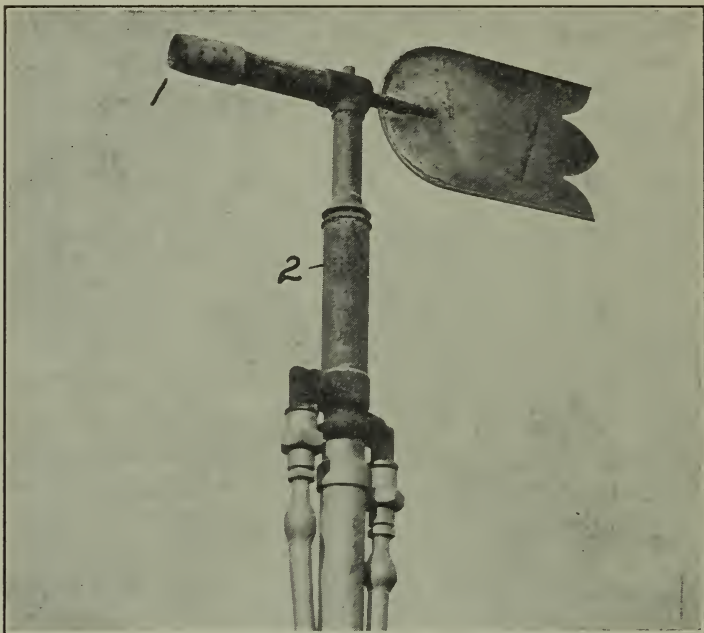


Plate XV. Dines Anemometer—Head

passed through such a record provides a way to determine average velocities in addition to gustiness.

Referring to Plates XV and XVI: There are two parts to the instrument; the head, Plate XV, exposed out of doors at a suitable place, and the recorder, Plate XVI, located indoors, and connected to the former with lead or iron pipes. The head, mounted on a rigid support, may be as much as 100 feet (30 m.) distant from the recorder. It is comprised of

two portions, (1) the pressure tube and the attached vane to direct the tube into the wind; and (2) the suction tube, with its wall drilled with a number of small holes through which the air has access to the annular space within. The constant of the instrument is determined largely by the number and size of these holes and the shape of the annular space. The connecting pipes transmit the suction and pressure to the outside and inside pipes respectively of a copper float resting in pure water at a certain height within the cylindrical tank (1) of the recorder, as shown by the glass gage (2). Plate (3), forming an airtight joint with the top of the float chamber, carries the record cylinder, rotated once each 24 hours by the clock within. Variations in the wind velocity cause corresponding changes in the suction and pressure, which combined, produce rises and falls of the float and the attached pen-arm (4).

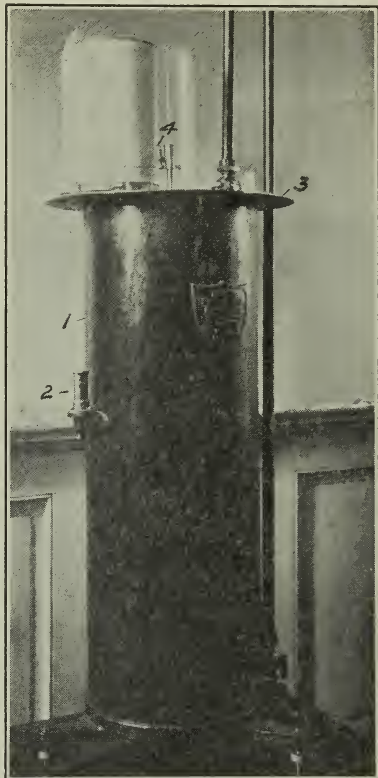


Plate XVI. Dines Anemometer—Recorder

Wind-velocity indicators are of two types: one utilizing a buzzer and push-button switch wired in series with a 2-cell dry battery placed within a box forming a part of the indicator; the other, Plate XII, more generally employed, having a buzzer, bell-ringing transformer, and, in the newer patterns, a small switch, and a rheostat all connected electrically to the

anemometer, the transformer taking the place of the battery. The rheostat is used to adjust the current to a strength just sufficient to operate the buzzer positively, thus protecting the anemometer contacts against injurious sparking. The electric circuits of the instrument are so devised that the number

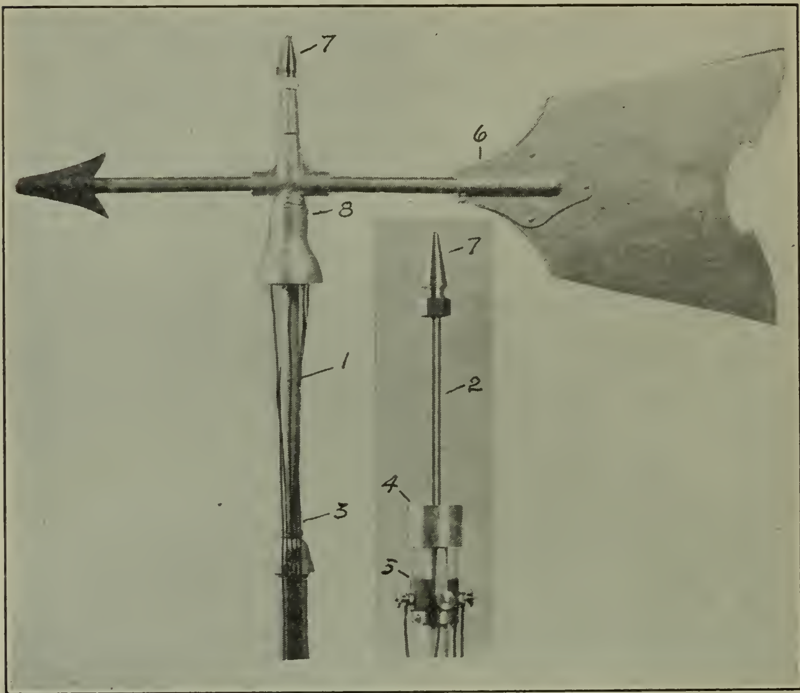


Plate XVII. Three-Foot Wind Vane and Contacting Bearing

of closures of the circuit per minute, as counted by an observer listening to the buzzer, corresponds to the wind velocity in miles per hour.

Wind vane and electrical contacts; wind-instrument supports. For general service at airways stations, the combined contacts and wind-vane bearing shown in Plate XVII are used. This device consists of a bearing housing (1) made of ½-

inch (13 mm.) pipe which screws into a fitting at the top of a pipe support. There are two bearings for the wind-vane axis (2) extending downward within the ½-inch (13 mm.) pipe: one formed by a keyway bushing at the upper end of the pipe; the second, a pivot bearing at (3). At (4) is a cam-equipped weather housing rigidly attached to the axis, and projecting into the housing is a set of four contact springs spaced 90° apart and assembled on the insulated ring (5) that fits over the pipe and is fastened thereto with a set screw. The wind vane (6) is clamped to the axis by nut (7). (8) is a thin aluminum shield which protects the contacts and springs from the weather. When electrically connected to the indicator (Plate XIII), directions are shown to eight points of the compass.

The metal vane, made with a flat tail of sheet aluminum, has an overall length of nearly 3 feet (1 m.).

At airport stations the wind-vane contacts are of the cam-collar type that are standard at first-order Weather Bureau stations, inclosed in a cast-iron box forming part of the 18-foot (5.5 m.) wind-instrument support. The contacts are turned by a 4-foot (1.2 m.) vane joined to its axis by a small pipe extending vertically from vane to contact box within the 2-inch (50 mm.) pipe forming the support.

Wind-instrument supports at airways stations. Two types of supports are used at these stations: (a) a 7-foot (2 m.) support of 1-inch (2.5 cm.) pipe for anemometer or contacting wind vane for exposure on beacon-light towers, and, (b), a 12-foot (3.5 m.) support of 1¼-inch (32 mm.) pipe for wind vane and anemometer for roof installations.

Pilot-Balloon Observations and Equipment

Observations of so-called pilot balloons give prompt and reliable information of both wind velocity and direction at flying altitudes. These balloons, made of pure rubber, are inflated with hydrogen just before use, to a diameter of about

30 inches (76 cm.) to give an ascensional rate of nearly 180 meters (about 600 ft.) per minute. After being released from the ground or roof of a building, as may be most convenient, the path of the balloon is carefully followed by means of one or two theodolites, usually one, and its position ob-

Plate XVIII. Balloon Filling Apparatus

served each minute until the balloon bursts, or it passes out of sight. The theodolite observations give the angular position of the balloon, and the altitude is known from the predetermined ascensional rate. These data are usually plotted immediately, the observer being in telephonic communication with an assistant located in the office at a plotting board, so

Plate XIX. Beginning of Flight of Pilot Balloon

Plate XX. Pilot Balloon Theodolite

that the wind directions and velocities at the several altitudes are found without delay by slide-rule computations and graphical methods, and thus made available for use quickly.

Balloon-filling apparatus. Referring to Plate XVIII, hydrogen from tank (1) flows under pressure to the three-

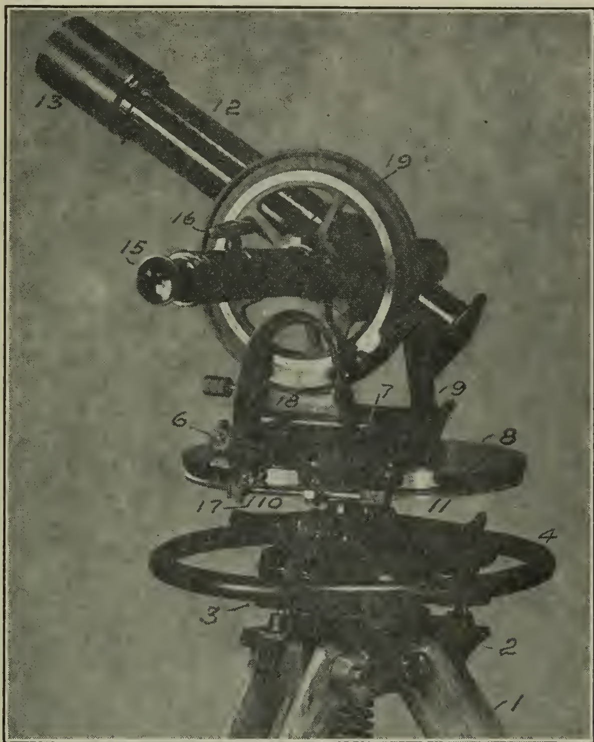


Plate XXI. Near View of Theodolite

way cock (2) which, when opened, permits the gas to pass through tubing (3) to the filler-nozzle (4) which fits the mouth of the balloon. The ascensional rate, e.g., 180 meters (600 ft.) per minute, having been determined upon, the balloon after preliminary kneading, etc., to make it pliable, is weighed on the trip scale (5). For the desired ascensional

rate mentioned, the free lift of a balloon weighing, for instance, 34 grams (1.2 oz.) must be 130 grams (4.6 oz.). The latter weight is placed in pan (6) below the balloon, and the balloon filled until it pulls the balance beam upward. Then the flow of gas from the tank is stopped by cock (2), and the balance brought into equilibrium by allowing a little of the gas to escape into the air. The balloon is then sealed and its dimensions taken. Plate XIX shows the beginning of a pilot-balloon flight.

The balloons are made in several colors, and one is chosen for the particular observation which will give it the greatest visibility as contrasted with the sky or clouds. Balloons may sometimes be followed for nearly an hour, and to elevations of 10 or 15 miles (15 to 25 km.). But it is knowledge of the conditions at flying altitudes up to 4,000 or 5,000 feet (1,200 to 1,500 m.) that is most valuable to the pilot, for it is quite frequently possible to gain a considerable advantage in speed and safety by choosing the proper flying altitude.

At night the balloon is made visible for observation by attaching to it a small Chinese lantern lighted by a paraffin candle or a small electric light.

Pilot-balloon theodolite. This instrument differs from any good transit principally in having a reflecting prism mounted within the telescope in such a manner as to bend the light rays at an angle of 90° to the axis of the telescope, thus directing them along the horizontal axis of the eye-piece tube.

Referring to Plates XX and XXI, the instrument proper is supported on a substantial white-ash tripod (1), surmounted by a bellmetal casting (2) with sockets for three leveling screws (3). In order to carry the instrument without injury to the delicate parts, handle (4) is used. The vertical axis of the theodolite is at (5), about which the baseplate is rotated after leveling, until oriented with the zero of the horizontal circle at true south. There are two levels, (6) and (7), with axes at right angles, the first on the baseplate (6),

the second on the telescope standard (9). Portions of the horizontal circle are observed at (10) and (11) with accompanying verniers by which readings may be made to degrees and hundredths, although tenths are in general sufficiently accurate. The vernier at (11) is added as a convenience to an observer who records readings of azimuth while another operates the theodolite. The telescope tube (12) has its lens in the outer end, protected by a cylindrical sleeve (13) called a sunshade, while the reflecting prisms are placed within the conical-shaped part (14). The eye-piece is located at (15), focused by rack and pinion operated by knurled-head (16). Both horizontal and vertical motions are made either by a free turning of the axis, or by a slow motion obtained by worm and worm-wheel. The worm, also called tangent screw, for motion in azimuth, is seen at (17); that for elevation at (18). Either of them may be meshed or unmeshed with its respective wheel. At (19) is the vertical circle with its vernier. Both the vertical and horizontal tubes are counterbalanced about their respective axes of rotation.

For night observations, the verniers and scales are lighted by flashlight bulbs, the electric current for the same being furnished by dry cells or by a small alternating-current transformer.

Equipment for Measuring Height of Ceiling

The so-called ceiling is the height of the under side of the lowest cloud layer above the ground at the point of observation. Accurate knowledge of this height, which is included in all airways observations, is of great importance, since the pilot as a rule flies beneath the clouds, rather than flying blind, especially if seeking a landing.

Measurement of the height of ceiling is accomplished in several ways, as follows:

(a) By pilot-balloon observations, the height being equal to the ascensional rate multiplied by the number of minutes

from the time of release until the balloon disappears or enters the lower cloud layer.

(b) By the small "ceiling" balloons filled with hydrogen for determining the daytime ceiling where pilot-balloon equipment is not available.

(c) At night by means of a ceiling-light projector, a form of electric searchlight which throws a spot of light on the underside of the cloud layer, the height of the light spot being found either by the use of an alidade or other ceiling-height indicator; or by elevating the beam to an angle, usually of 45° with the horizontal, but sometimes 63° 26′, and measuring the horizontal distance from the projector to a point where the light spot is in the zenith. For a 45° elevation, the distance is equal to the height of the ceiling; for 63° 26′ angle, the height is twice the distance measured.

Ceiling-light projector. Referring to Plate XXII, the projector drum is made of an aluminum alloy mounted on a pedestal with trunions which permit of the accurate elevation of the beam from 45° to the vertical, which latter is sometimes employed when the beam must penetrate smoky or hazy atmosphere, such as found near the large cities. The projectors are usually 14 inches (36 cm.) in diameter, although larger sizes are also in service where needed, and the condensed-filament electric lamps employed vary in power from 250 to 1,500 watts, but are ordinarily 250 for level, smoke-free locations. Peep sight holes in the drum are so arranged as to allow of the careful focusing of the lamp with respect to the 4¾-inch (120 mm.) focus parabolic mirror within the drum. A concentric stray-light shield confines the beam of light to a narrow diameter, so that the light spot is sufficiently definite in form.

The projector is so made as to mount readily on a 4-inch (100 mm.) pipe pedestal with screw companion flanges or flange unions at top and bottom; the lower to fasten to the deck, the upper to the projector flange. For ground exposures,

a longer pipe extends into the ground, as a rule, being held rigid by means of a block of concrete and by tamping about the pipe.

An **alidade** for direct measurement of ceiling heights is shown in Plate XXII. It is designed for the direct reading of the heights when the light beam is projected at an angle of 63° 26′ to the horizontal. The device consists of a bronze

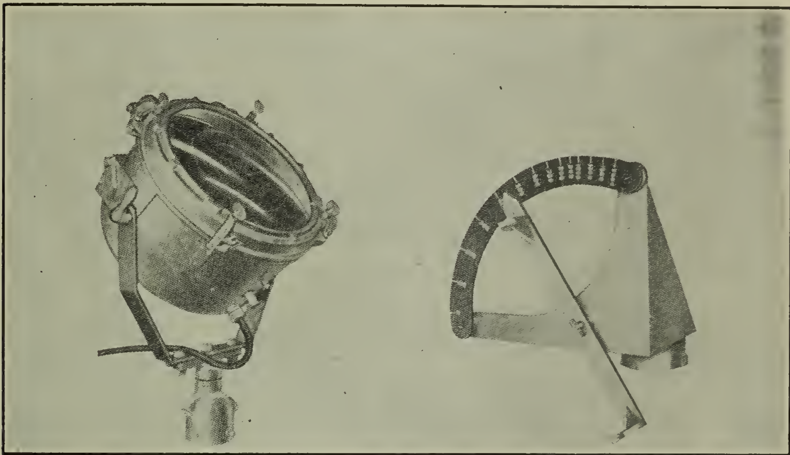


Plate XXII. Ceiling Light Projector (*left*) and Alidade (*right*)

quadrant with readings of ceiling height engraved thereon. The quadrant is mounted on a 4-inch (100 mm.) standard pipe support, either set in the ground or secured to a deck with bolts or lag screws. A universal joint provides for leveling, and triangular sights on a movable arm enable the observer to sight on the light spot on the clouds; then the arm is clamped in place and the height read on the scale.

Exposure of Instruments

In order that they may function properly, it is necessary that all instruments be so exposed as to indicate as nearly as possible the local conditions, unaffected by such influences as

buildings, trees, and other obstructions. In general, the methods that have been adopted as standard by all meteorological services are used at airport and airways stations, but there are some variations in detail, especially at airports, in order to eliminate hazards to flying that would be caused, for example, by a wind-instrument tower extending much above the highest part of the hangars or other buildings. The details vary in individual cases, but general specifications for installations, including wiring, lighting, etc., as well as for suitable quarters for the service, can be obtained from the U. S. Weather Bureau, Washington, D. C.

CHAPTER 3

VERTICAL STRUCTURE OF THE ATMOSPHERE

Troposphere and stratosphere. A vertical section of the atmosphere from the equator to either pole would show, as its most distinctive feature, a marked contrast between the lowest 10 to 15 kilometers (33,000 to 50,000 ft.) and the region above those levels, with a sharp line of demarcation between the two. The lower region is known as the *troposphere* and the upper, as the *stratosphere.* The troposphere is characterized in general by decreasing temperatures with altitude, amounting on the average to 6° C. per kilometer (3.3° F. per 1,000 ft.) and by considerable cloudiness; the stratosphere, by little vertical change in temperature and by no cloudiness. The height of the dividing surface, sometimes called the *tropopause,* varies from 17 kilometers (56,000 ft.) in the tropics to about 8 or 9 kilometers (26,000 to 30,000 ft.) in the polar regions; in the United States and Europe it is between 11 and 12 kilometers (36,000 to 40,000 ft.). It is also greater in summer than in winter and above high than above low surface pressure. The temperature of the stratosphere varies inversely with the height of its base, being lowest, about −80° C. (−112° F.), over the tropics, and increasing to about −55° C. (−67° F.) in latitudes 40° to 50°; also it is lower above high than above low surface pressure.

Interest in the stratosphere, so far as aeronautics is concerned, at the present time at least, is largely academic. Suffice it to say that, according to Humphreys, Gold, and others, the conditions in the stratosphere are determined by the balance between incoming and outgoing radiation, and in order that this balance may be maintained, it is necessary that the

temperature be essentially constant at all heights in the stratosphere. In the following sections, attention will be confined for the most part to the troposphere, particularly to the lowest 5 kilometers (16,000 ft.).

Cause of temperature decrease with altitude in the troposphere. The change of temperature with altitude is primarily due to dynamic heating and cooling. By this is meant that, if air is compressed, work is done on it and its temperature is raised, and if expanded, it does work and is cooled. A familiar example of heating due to compression occurs when air is forced into a tire by an automobile pump. During this process the barrel of the pump is likely to become too hot to touch. Conversely, if air expands, it gives up heat, or in other words becomes cool itself. As will be explained later, air pressure and therefore air density diminishes with altitude. Hence, ascending air expands and descending air is compressed. In the case of unsaturated air, if not materially affected by gain of heat from the surrounding air or by loss of heat to it, the expansion when rising, and contraction when falling are such that a change in temperature of approximately 1° C. per 100 meters (about 5.5° F. per 1,000 ft.) change in altitude is produced. This change is known as the "adiabatic rate," and may be briefly defined as the change in temperature brought about by a change in density, or, in other words, the actual temperature of the mass of air under consideration is changed, but its potential temperature (temperature due to position) remains unchanged. Under such ideal conditions any mass of air that may be moved up or down will remain in its new position, because its condition of equilibrium, i.e., its potential energy, has not been changed. If, however, the temperature change with height, or "lapse rate," as it is now generally called, is less than the adiabatic rate, air that is moved upward will cool to a lower temperature than that of the air with which it comes in contact and will therefore fall back to its initial level; if the lapse rate

is greater than the adiabatic, the lower portions of the air will ascend and the upper portions descend until the lapse rate of the whole mass has returned to the adiabatic. In these three states air is in neutral, stable, and unstable equilibrium respectively, the degree of stability or instability being proportional to the extent of the variation from the adiabatic rate. In the lower levels the air is most stable as a rule on calm, clear nights and most unstable on bright, hot afternoons. The three states of equilibrium are shown in Figure 9.

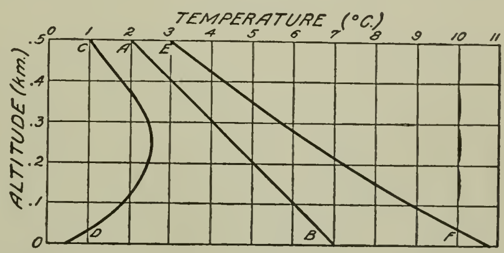


Figure 9. Examples of Different States of Equilibrium: *AB,* Adiabatic (Neutral Equilibrium); *CD,* Inversion (Stable Equilibrium); *EF,* Superadiabatic (Unstable Equilibrium)

To convert kilometers to feet, multiply by 3,300; ° C. to ° F., multiply by 1.8 and add 32.

Effects of moisture. The atmosphere is never entirely free from moisture, and as the specific heat of water vapor is nearly twice that of dry air, it is evident that the adiabatic rate of temperature will diminish in proportion to the amount of water vapor present; moreover, as the capacity of air[1] for water vapor is a function of its temperature, the adiabatic rate of moist air also diminishes with increasing temperature. This decrease is very small for all conditions of humidity until saturation, i.e., condensation of the water vapor, occurs. When this state is reached, a marked decrease in the adiabatic rate takes place, owing to the "latent heat of vaporization" or "latent heat of fusion" that is set free.

[1] Although it is customary to speak of the capacity of air for water vapor, in reality the air itself has practically no effect in this respect, except in so far as its temperature affects that of the water vapor. In other words, a cubic foot or a cubic meter of space without air can contain essentially the same amount of water vapor as it can if air is present, providing the temperature is the same in both cases.

In order to grasp the significance of this effect of moisture on the adiabatic rate, it is essential to know the meaning of the expression "latent heat." Briefly, it represents the energy, or work, required to change any substance from the solid to the liquid state, or from the liquid to the gaseous state. This change from one state to another is not accompanied by a change in temperature, the heat used being merely a form of energy by means of which the change is brought about. But, when the reverse process occurs, this stored up energy is released as sensible heat and there is consequently a rise in temperature or a decrease in the rate of fall. Thus, when water is converted into water vapor, no temperature change occurs, but, when this water vapor condenses as fog, cloud, rain, etc., the so-called latent heat is given up, and the temperature of the air rises or, if previously falling, its rate of fall diminishes. The energy given up when water changes from the gaseous to the liquid state is called latent heat of vaporization; when from the liquid to the solid state, latent heat of fusion; when from the gaseous directly to the solid, that is, at temperatures below freezing, both forms are liberated.

Air, in rising, sooner or later reaches a height at which its reduced temperature causes condensation of water vapor and consequent setting free of latent heat. Conversely, when air in which condensation has already taken place descends, it becomes warmed dynamically to a temperature at which evaporation and therefore absorption of heat occurs. However, in the case of descending air in which condensation does not exist, its temperature continues to rise until it reaches a level of the same temperature as that which it has acquired itself. Since descending air on the average is drier than ascending, because of the rain, etc., that has fallen out of the latter, the adiabatic lapse rate for dry air holds to a greater height, as a rule, in descending than in ascending air.

Temperatures in the lower half of the troposphere. As already stated, the normal change of temperature with alti-

tude in the troposphere is a decrease amounting to about 6° C. per kilometer (3.3° F. per 1,000 ft.) in all parts of the world. It is largest, about 7° C. per km. (3.9° F. per 1,000 ft.), between 5 and 10 kilometers (16,000 to 33,000 ft.) and in this region it is quite uniform throughout the year and from day to day. In the lowest 5 kilometers (16,000 ft.) it amounts

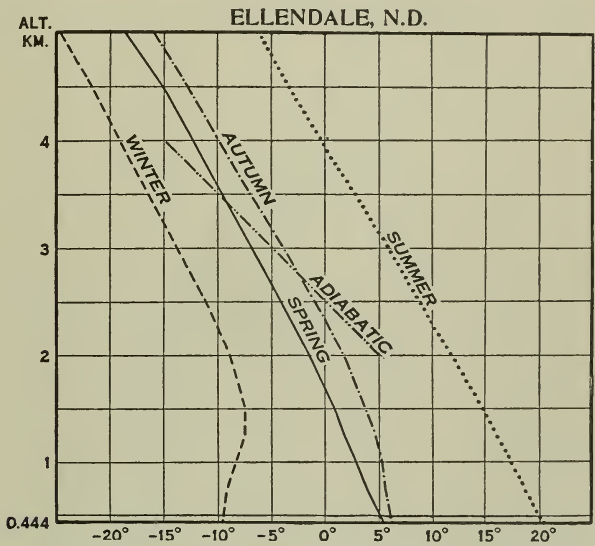


Figure 10. Average Seasonal Upper Air Temperatures, ° C., at Ellendale, North Dakota

To convert kilometers to feet, multiply by 3,300; ° C. to ° F., multiply by 1.8 and add 32.

to about 5° C. per km. (2.7° F. per 1,000 ft.) but is exceedingly irregular, varying from a strongly inverted condition (increase with altitude) to slightly above the dry air adiabatic rate (1° C. per 100 m. or 5.5° F. per 1,000 ft.). The latter condition occurs only for brief periods and through short intervals of altitude, usually in the hottest part of the day and immediately above the surface. Inversions are most pronounced when net loss by radiation is large, as at night or in the interior of continents during winter. They also occur

as the result of importation of warm air above cold and the underrunning of cold currents at the surface, owing to different wind directions at various levels and as a result of strong surface winds. Figures 10 and 11 show the average seasonal lapse rates at Ellendale, N. Dak., and Groesbeck, Tex. These also indicate the greater annual range at all levels in the north-

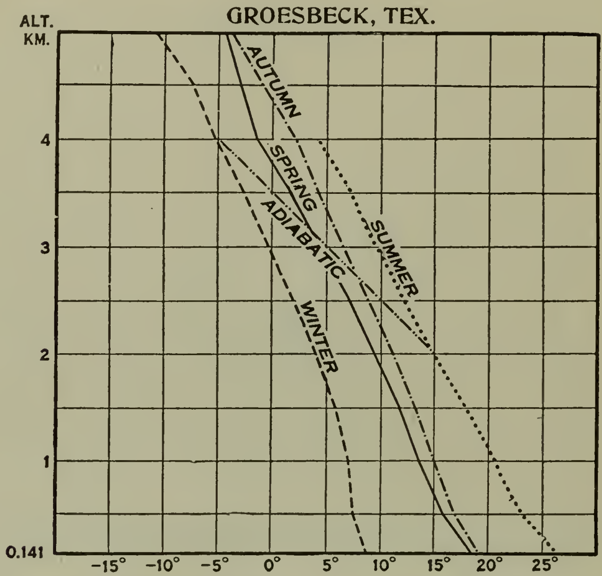


Figure 11. Average Seasonal Upper Air Temperatures, ° C., at Groesbeck, Texas

To convert kilometers to feet, multiply by 3,300; ° C. to ° F., multiply by 1.8 and add 32.

ern part of the country than in the southern, as well as the rather small decrease in this range from the surface up to 5 kilometers (16,000 ft.).

The latitudinal range in temperature at the surface for July and January has already been shown in Figures 1 to 4. That a similar marked difference persists at upper levels is indicated in Figures 12 and 13. Close relationship exists between these gradients and the seasonal differences in strength of winds, as will be shown later (Figures 57 and 58).

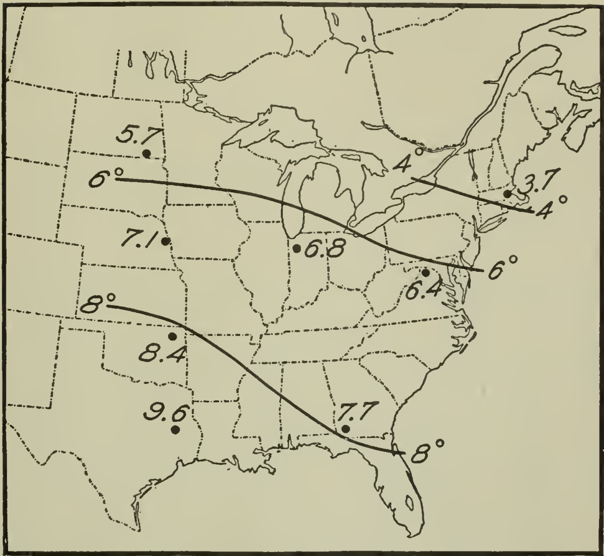


Figure 12. Average Summer Temperatures, ° C., in Eastern and Central United States at 3 kilometers (10,000 ft.) Above Sea Level

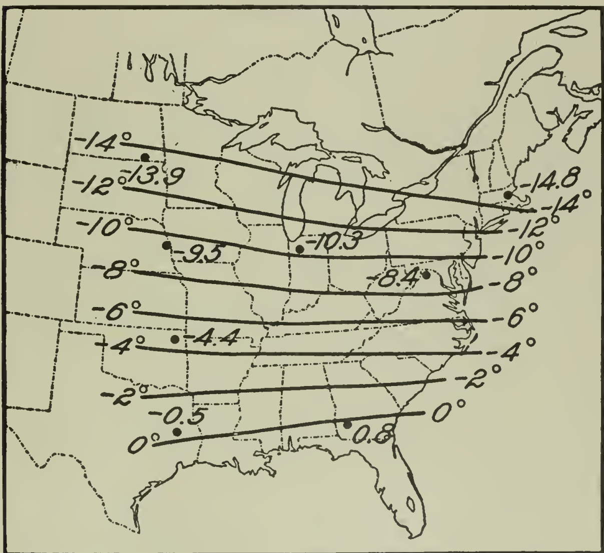


Figure 13. Average Winter Temperatures, ° C., in Eastern and Central United States at 3 kilometers (10,000 ft.) Above Sea Level

To convert ° C. to °F., multiply by 1.8 and add 32.

The highest and lowest temperatures ever recorded at different levels in summer and winter at these two stations, based on a ten-year record, are given in Table 1.

TABLE 1. HIGHEST AND LOWEST TEMPERATURES, ° C. AND ° F., IN SUMMER AND WINTER AT ELLENDALE, N. DAK., AND GROESBECK, TEX.

ELLENDALE, N. DAK.

Altitude M.S.L.		Summer				Winter			
		Highest		Lowest		Highest		Lowest	
m.	ft.	° C.	° F.	° C.	° F.	° C.	° F.	° C.	° F.
444*	1,460	34.0	93.2	7.5	45.5	10.9	51.6	−31.3	−24.3
500	1,600	33.4	92.1	6.8	44.2	10.6	51.1	−30.8	−23.4
1,000	3,300	32.0	89.6	0.8	33.4	13.0	55.4	−33.7	−28.7
2,000	6,600	25.7	78.3	−2.6	27.3	9.8	49.6	−33.6	−28.5
3,000	9,800	18.0	64.4	−6.8	19.8	3.6	38.5	−36.8	−34.2
4,000	13,100	10.2	50.4	−10.3	13.5	−3.4	25.9	−32.6	−26.7

GROESBECK, TEX.

Altitude M.S.L.		Summer				Winter			
		Highest		Lowest		Highest		Lowest	
m.	ft.	° C.	° F.	° C.	° F.	° C.	° F.	° C.	° F.
141*	460	37.1	98.8	12.8	55.0	26.4	79.5	−9.2	15.4
500	1,600	31.9	89.4	10.8	51.4	22.8	73.0	−12.9	8.8
1,000	3,300	27.0	80.6	8.4	47.1	22.4	72.3	−17.6	0.3
2,000	6,600	22.1	71.8	4.8	40.6	17.6	63.7	−11.6	11.1
3,000	9,800	15.7	60.3	0.6	33.1	11.2	52.2	−14.6	5.7
4,000	13,100	8.6	47.5	−4.4	24.1	5.1	41.2	−13.1	8.4

* Surface.

These figures indicate that, even in the northern part of the country, temperatures at ordinary flying levels seldom reach the freezing point in summer and are little lower than those at the surface in winter.

The diurnal range of temperature, characteristic of the surface, disappears almost altogether at 1 to 1½ kilometers (3,300 to 4,900 ft.). Above that level the phase remains nearly the same as at the surface, but the amplitude is very small, amounting on the average to about 1° C. (2° F.). The following values give the times of occurrence of highest and

lowest and the daily range at different levels above Drexel (near Omaha), Neb.:

Drexel, Neb.

Altitude M.S.L.		Summer				Winter			
		Time of		Range		Time of		Range	
m.	ft.	Highest	Lowest	° C.	° F.	Highest	Lowest	° C.	° F.
396*	1,300	3 P.M.	5 A.M.	10.3	18.5	3 P.M.	7 A.M.	8.6	15.5
500	1,600	4 P.M.	5 A.M.	8.1	14.6	3 P.M.	8 A.M.	5.1	9.2
750	2,500	4 P.M.	8 A.M.	4.8	8.6	4 P.M.	8 A.M.	2.7	4.9
1,000	3,300	6 P.M.	9 A.M.	2.8	5.0	5 P.M.	8 A.M.	1.5	2.7
1,500	4,900	6 P.M.	7 A.M.	0.9	1.6	4 P.M.	6 A.M.	0.8	1.4
2,000	6,600	4 P.M.	4 A.M.	0.6	1.1	4 P.M.	3 A.M.	1.2	2.2
2,500	8,200	7 P.M.	5 A.M.	0.9	1.6	3 P.M.	2 A.M.	1.3	2.3
3,000	9,800	6 P.M.	9 A.M.	0.5	0.9	12 MDT.	2 A.M.	1.3	2.3
3,500	11,500	10 P.M.	2 P.M.	0.5	0.9	9 P.M.	7 A.M.	1.0	1.8

* Surface.

Humidity. *Absolute humidity* is the actual amount of water vapor in the air. The total possible amount, i.e., at saturation, increases rapidly with temperature. For example, the weight at 0° C. (32° F.) is 4.8 grams per cubic meter (2.1 gr./ft.^{3}); at 15° C. (59° F.), 12.8 grams per cubic meter (5.6 gr./ft.^{3}); and at 30° C. (86° F.), 30.4 grams per cubic meter (13.3 gr./ft.^{3}). Absolute humidity is often expressed in terms of the expansive force that the vapor exerts and is then referred to as *vapor pressure,* measured in the same units employed for barometric pressure. *Relative humidity* is the amount of water vapor present at any one time as compared with the amount at saturation and is expressed as a percentage. Relative humidity is very irregular, but on the average decreases from about 70% at the surface to about 50% at 4 or 5 kilometers (13,000 to 16,000 ft.). In general it is higher in the southern states than in the northern during summer and vice versa during winter. *Dew-point* is the temperature at which, without change of pressure, the air is saturated.

Since vapor pressure varies with the temperature and relative humidity, both of which decrease with altitude on the average, its change with altitude is also a sharp decrease in summer and a more moderate one in winter; this decrease is more pronounced in all seasons in the southern than in the northern states. These characteristics of the vertical changes are shown in Figures 14 and 15.

Pressure. The pressure at any altitude is, in large part, a function of the surface pressure, the mean temperature of the air column and the water vapor. Other factors, such as variation of gravity with latitude and altitude, are not ordinarily considered, except in very precise altitude determinations. The usual statement of the pressure-altitude relation, disregarding unimportant factors, is [2]

$$\log P = \log P_0 - \frac{Z}{K\left(1 + \alpha\theta + 0.378\frac{e}{P}\right)}$$

in which

P = the pressure to be determined.
P_0 = that at some lower station.
Z = the difference in altitude between the two stations.
K = the barometric constant.
α = the coefficient of expansion of air.
θ = the mean temperature of the air column.

and

$\frac{e}{P}$ = the ratio of the partial pressure of the water vapor to the total pressure.

In this equation K and α are constants (18,400 m. and 0.00367 for 1° C., respectively) 0.378 e/P is ordinarily small, and, for a given altitude, Z is, of course, a constant. There-

[2] This is, in shortened form, the well-known Laplacian hypsometric equation. Full discussions of its derivation and use may be found in numerous publications, some of the more recent being: "Physics of the Air," by W. J. Humphreys; "The Determination of the Altitude of Aircraft," by W. G. Brombacher, published in *Journal of the Optical Society of America and Review of Scientific Instruments*, Vol. 7, No. 9, pp. 719-774, September, 1923; "Smithsonian Meteorological Tables," 4th revised edition, 1918, p. xxxix—*et seq.*

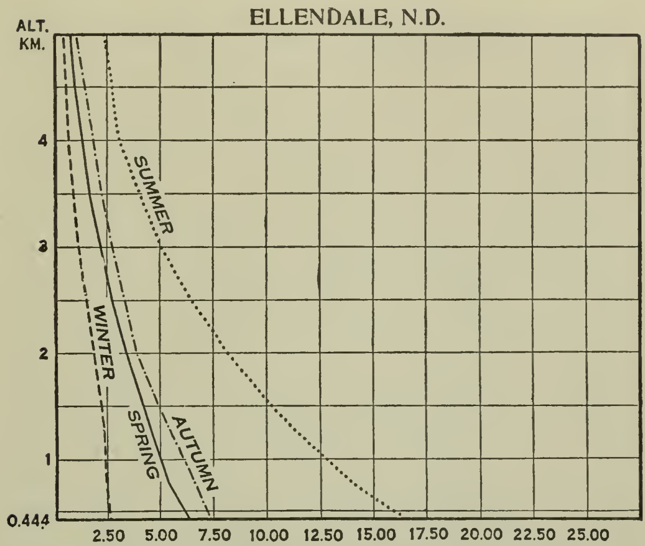


Figure 14. Average Seasonal Upper Air Vapor Pressures, mb., at Ellendale, North Dakota

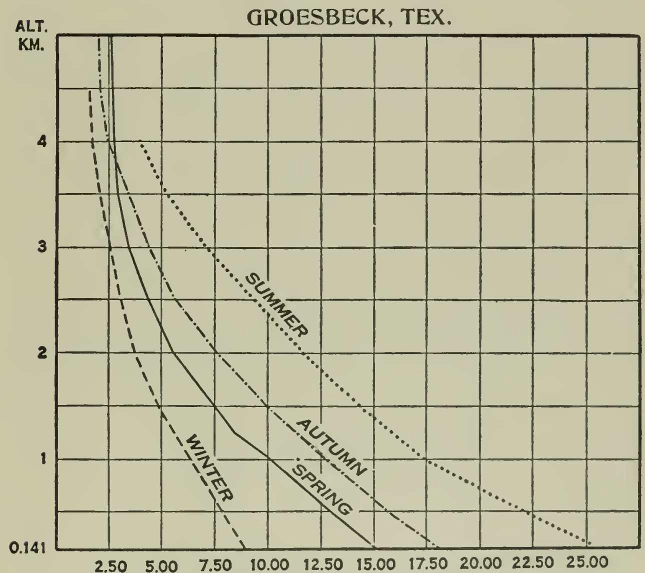


Figure 15. Average Seasonal Upper Air Vapor Pressures, mb., at Groesbeck, Texas

To convert kilometers to feet, multiply by 3,300; millibars to millimeters and inches, multiply by 0.75006+ and 0.02953+, respectively.

fore, P varies principally with changes in P_0 and θ. When Z is small, P_0 is the more important; when it is large, i.e., as the altitude increases, θ exercises the larger effect. On the average then, at ordinary flying levels there is a pressure gradient from the tropics poleward. It is much more pronounced in winter than in summer, owing to the greater latitudinal contrast in temperature in the former season; in this season also the upper air pressures themselves at all latitudes are much lower than in summer. At sea level, as stated earlier and as shown in Figures 5 and 6, the annual variation consists of higher pressure over continents in winter than in summer with a corresponding decrease over the oceans. The difference between summer and winter pressures at 3 kilometers (10,000 ft.) is shown in Figures 16 and 17. The intimate relation between upper air pressures and temperatures is brought out by a comparison of these figures with Figures 12 and 13.

Density.[3] Atmospheric density varies directly with the pressure of the air and inversely with the temperature and moisture content. Expressed mathematically:

$$\rho = \rho_0 \frac{P - 0.378e}{P_0} \times \frac{T_0}{T}$$

in which

ρ is the density to be determined.
ρ_0 is the density of dry air at pressure P_0 and temperature T_0.
P and T are the given pressure and temperature respectively, and
e is the vapor pressure.

In simplified form this becomes

$$\rho = 0.46446 \times \frac{P - 0.378e}{273 + t}$$

[3] Specific weight. See footnote 3 in Introduction.

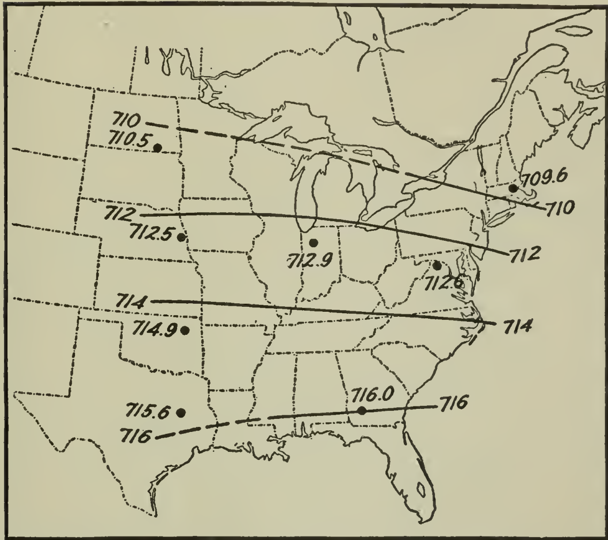


Figure 16. Average Summer Pressures, mb., in Eastern and Central United States at 3 kilometers (10,000 ft.) Above Sea Level

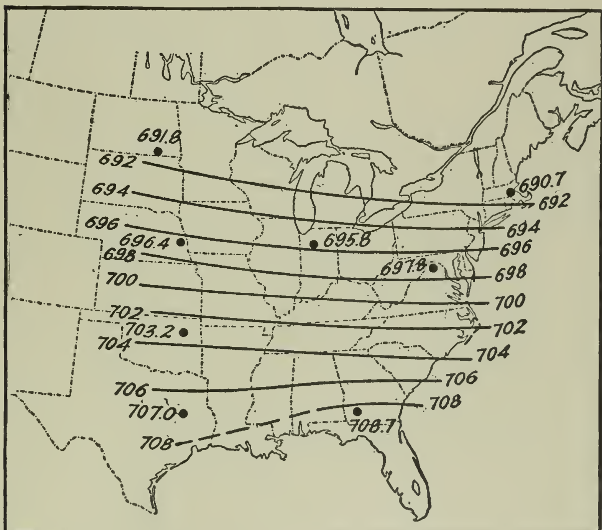


Figure 17. Average Winter Pressures, mb., in Eastern and Central United States at 3 kilometers (10,000 ft.) Above Sea Level

To convert millibars to millimeters and inches, multiply by 0.75006+ and 0.02953+, respectively.

in which ρ is expressed in kg./m.^{3},
P and e in millimeters,
and t in degrees centigrade;

Or,

$$\rho = 0.34836 \times \frac{P - 0.378e}{273 + t}$$

in which P and e are expressed in millibars;

Or,

$$\rho = 1.3245 \times \frac{P - 0.378e}{459 + t}$$

in which ρ is expressed in lb./ft.^{3},
P and e in inches,
and t in degrees Fahrenheit.

The annual range in density at the surface is on the average about 10%. The range from day to day is occasionally as large as this, owing to changes in pressure and temperature, and the extreme range for the entire year may be 20% or more. It is higher in the temperate than in the torrid or arctic zones, higher at lowland than at mountain stations and much higher over the land than over the oceans. Figures 18 and 19 show the summer and winter means at sea level for the eastern part of the United States. The relation to temperature is well brought out by reference to Figures 3 and 4.

The range is much less above the earth's surface because, as previously stated, higher pressures accompany and in fact, are the result of higher temperatures at those altitudes and the two offset each other in their effect upon densities. Figures 20 and 21 show the small range at 3 kilometers (10,000 ft.). There is a further decrease with height until at about 8 kilometers (26,000 ft.) density is constant throughout the year and in all parts of the world. Above this level it is higher in summer than in winter and also in low latitudes than in high.

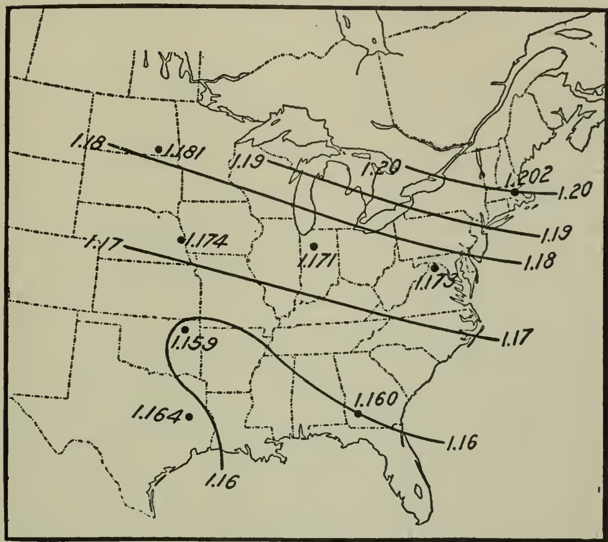


Figure 18. Average Summer Densities, kg./m.^{3}, at Sea Level in Eastern and Central United States

To convert kg./m.^{3}, to lb./ft.^{3}, multiply by 0.06243.

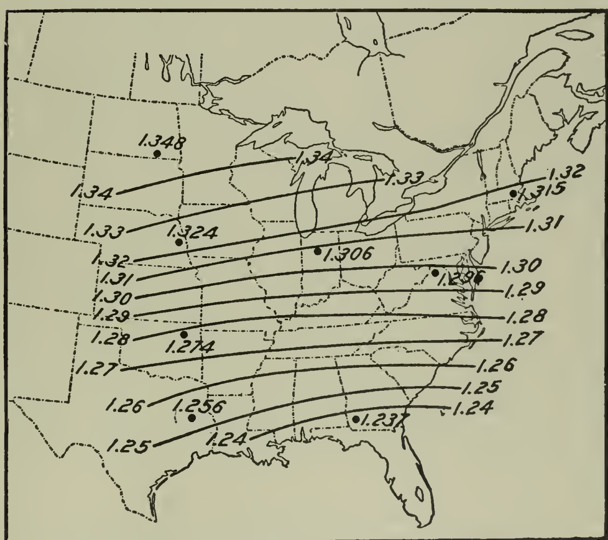


Figure 19. Average Winter Densities, kg./m.^{3}, at Sea Level in Eastern and Central United States

To convert kg./m.^{3}, to lb./ft.^{3}, multiply by 0.06243.

Average conditions at latitude 40° in the United States. At the request of the National Advisory Committee for Aeronautics a report was prepared in 1922 for the purpose of determining how closely the average conditions in the United States are in agreement with those proposed by Toussaint for general adoption as a "standard atmosphere." [4] In this study use was made of all available data obtained by means of kites and balloons at several stations near latitude 40°, this being approximately midway between the northern and southern limits of the country. These values were found to be sufficiently in accord with Toussaint's "standard atmosphere" to justify the National Advisory Committee for Aeronautics in adopting the latter, with slight modifications, for use throughout the United States.

In Table 2 are presented the results of this study, values being given in both metric and English units (temperatures in ° C., °A. and ° F.). The figures in the first column under "Density" are based on the standard value for dry air, 1,293 kilograms per cubic meter or 0.08072 pounds per cubic foot at a pressure of 1,013.3 millibars (760 mm. or 29.92 in.), and a temperature of 0° C. (32° F. or 273° A.). The figures in the second column under "Density" have been obtained by multiplying those in the first by 1.293 (for values in metric units) or 0.08072 (for values in English units).

It will be noted that the mean temperatures in the stratosphere are the same for summer and winter. Although this is probably not strictly true, the amount of data is not sufficient to establish the seasonal difference with accuracy at these upper levels. The value −55° C. (−67° F.) for the year agrees closely with European results. The range between summer and winter probably is less than 5° C. (9° F.) for the mean.

[4] W. R. Gregg, "Standard Atmosphere," National Advisory Committee for Aeronautics Report No. 147, 1922.

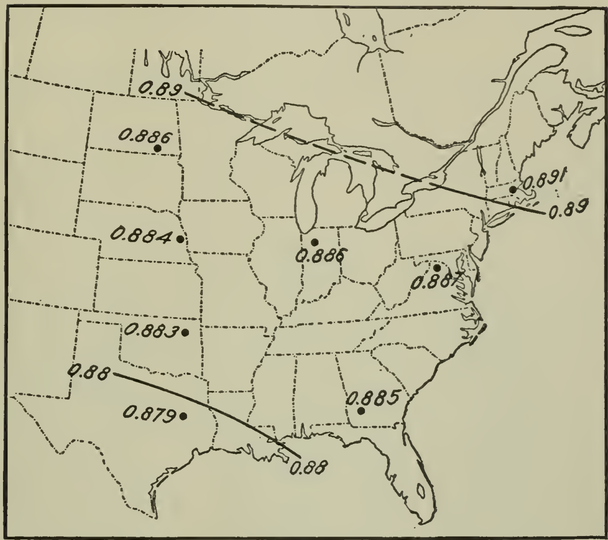


Figure 20. Average Summer Densities, kg./m.^{3}, at 3 kilometers (10,000 ft.) Above Sea Level in Eastern and Central United States

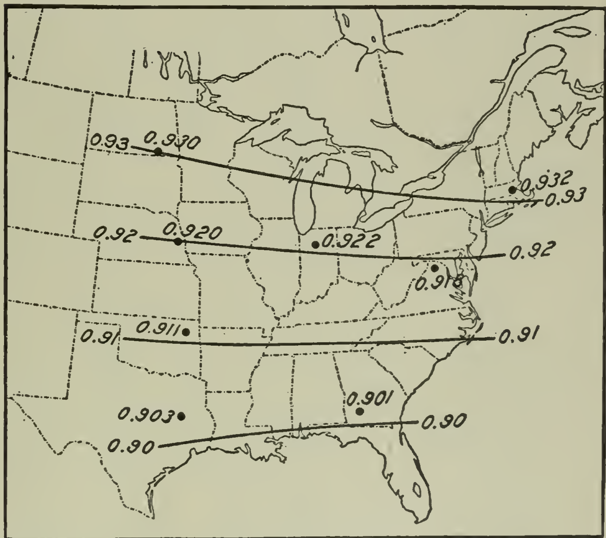


Figure 21. Average Winter Densities, kg./m.^{3}, at 3 kilometers (10,000 ft.) Above Sea Level in Eastern and Central United States

To convert kg./m.^{3}, to lb./ft.^{3}, multiply by 0.06243.

TABLE 2. MEAN UPPER AIR BAROMETRIC AND VAPOR PRESSURES, TEMPERATURES AND DENSITIES AT ABOUT LATITUDE 40° IN U. S.
METRIC UNITS

Altitude M. S. L.	Pressure		Temperature		Vapor Pressure		Density	
m.	mb.	mm.	° C.	° A.	mb.	mm.	Per Cent Standard	Kilograms per Cubic Meter
SUMMER								
0	1,014.0	760.5	25.0	298.0	22.0	16.5	90.9	1.175
500	957.5	718.0	22.0	295.0	17.5	13.0	86.8	1.123
1,000	904.0	678.0	19.0	292.0	14.0	10.5	82.9	1.072
1,500	852.5	639.5	16.0	289.0	11.0	8.5	79.1	1.023
2,000	803.5	602.5	13.0	286.0	8.5	6.5	75.4	0.975
3,000	713.0	535.0	7.0	280.0	5.0	4.0	68.4	.885
4,000	630.5	473.0	0.5	273.5	3.5	2.5	62.0	.801
5,000	556.0	417.0	−5.5	267.5	2.0	1.5	55.9	.723
6,000	488.5	366.5	−12.5	260.5	1.0	1.0	50.5	.653
8,000	373.5	280.0	−26.0	247.0			40.7	.527
10,000	281.0	211.0	−39.0	234.0			32.4	.418
12,000	208.5	156.5	−52.0	221.0			25.4	.329
14,000	152.5	114.5	−55.0	218.0			18.8	.244
16,000	111.5	83.5	−55.0	218.0			13.8	.178
18,000	81.5	61.0	−55.0	218.0			10.1	.130
20,000	59.5	44.5	−55.0	218.0			7.4	.095
WINTER								
0	1,020.0	765.0	−2.0	271.0	4.5	3.5	101.2	1.309
500	957.5	718.0	−3.0	270.0	3.5	2.5	95.4	1.234
1,000	899.0	674.5	−3.0	270.0	3.0	2.5	89.6	1.159
1,500	844.0	633.0	−4.0	269.0	2.5	2.0	84.4	1.092
2,000	792.0	594.0	−5.0	268.0	2.0	1.5	79.6	1.029
3,000	697.0	523.0	−9.0	264.0	1.5	1.0	71.0	0.918
4,000	611.5	458.5	−14.5	258.5	1.0	1.0	63.7	.823
5,000	535.0	401.5	−20.5	252.5	0.5	0.5	57.1	.738
6,000	466.5	350.0	−27.5	245.5			51.2	.662
8,000	350.5	263.0	−41.0	232.0			40.7	.526
10,000	259.5	194.5	−50.0	223.0			31.4	.405
12,000	190.5	143.0	−54.0	219.0			23.4	.303
14,000	139.5	104.5	−55.0	218.0			17.2	.223
16,000	102.0	76.5	−55.0	218.0			12.6	.163
18,000	74.5	56.0	−55.0	218.0			9.2	.119
20,000	54.5	41.0	−55.0	218.0			6.7	.087
ANNUAL*								
0	1,017.0	763.0	11.5	284.5	11.5	8.5	95.9	1.240
500	957.5	718.0	9.5	282.5	9.5	7.0	91.0	1.176
1,000	901.5	676.0	8.0	281.0	7.5	5.5	86.2	1.114
1,500	848.5	636.5	6.0	279.0	6.0	4.5	81.7	1.056
2,000	798.0	598.5	4.0	277.0	5.0	4.0	77.4	1.001
3,000	705.0	529.0	−1.0	272.0	3.0	2.5	69.7	0.902
4,000	621.0	466.0	−7.0	266.0	2.0	1.5	62.8	.813
5,000	546.0	409.5	−13.0	260.0	1.0	1.0	56.5	.731
6,000	478.0	358.5	−20.0	253.0	0.5	0.5	50.8	.657
8,000	362.0	271.5	−33.5	239.5			40.7	.527
10,000	270.5	203.0	−44.5	228.5			31.9	.412
12,000	199.5	149.5	−53.0	220.0			24.4	.316
14,000	146.0	109.5	−55.0	218.0			18.0	.233
16,000	107.0	80.5	−55.0	218.0			13.2	.171
18,000	78.0	58.5	−55.0	218.0			9.6	.125
20,000	57.0	43.0	−55.0	218.0			7.0	.091

*The annual means also represent quite closely the average spring and autumn conditions.

Table 2 (*Continued*)
English Units

Altitude M. S. L. ft.	Pressure in.	Temperature ° F.	Vapor Pressure in.	Density Per Cent Standard	Density Pounds per Cubic Foot
SUMMER					
0	29.94	77.0	0.65	90.9	0.0734
1,000	28.92	73.5	.57	88.4	.0714
2,000	27.92	70.5	.50	85.9	.0694
3,000	26.95	67.0	.43	83.6	.0674
4,000	26.01	64.0	.37	81.2	.0655
5,000	25.10	60.5	.32	78.9	.0637
6,000	24.22	57.0	.27	76.7	.0619
7,000	23.35	54.0	.23	74.4	.0600
8,000	22.52	50.5	.20	72.3	.0583
9,000	21.71	47.5	.17	70.1	.0566
10,000	20.92	44.0	.15	68.0	.0549
12,000	19.42	37.0	.12	64.1	.0517
14,000	18.00	30.0	.09	60.3	.0487
16,000	16.67	23.5	.06	56.6	.0457
18,000	15.42	16.0	.05	53.2	.0429
20,000	14.24	8.5	.03	49.9	.0403
25,000	11.61	−10.5		42.5	.0343
30,000	9.39	−28.0		35.7	.0288
35,000	7.53	−46.0		29.9	.0241
40,000	5.97	−62.5		24.7	.0199
45,000	4.71	−67.0		19.7	.0159
50,000	3.71	−67.0		15.5	.0125
55,000	2.92	−67.0		12.2	.0099
60,000	2.30	−67.0		9.6	.0078
65,000	1.81	−67.0		7.6	.0061
WINTER					
0	30.12	28.5	0.13	101.2	0.0817
1,000	28.99	27.5	.11	97.6	.0788
2,000	27.89	26.5	.10	94.1	.0760
3,000	26.84	26.5	.09	90.6	.0731
4,000	25.82	26.0	.08	87.2	.0704
5,000	24.84	24.5	.07	84.2	.0679
6,000	23.90	23.5	.06	81.2	.0655
7,000	22.99	22.0	.06	78.4	.0632
8,000	22.12	20.0	.06	75.7	.0611
9,000	21.27	17.5	.05	73.2	.0591
10,000	20.45	15.5	.04	70.6	.0570
12,000	18.89	9.5	.03	66.1	.0534
14,000	17.44	3.0	.02	61.9	.0500
16,000	16.07	−3.5	.01	57.9	.0467
18,000	14.80	−11.0		54.2	.0437
20,000	13.60	−18.5		50.6	.0409
25,000	10.95	−37.5		42.6	.0344
30,000	8.73	−52.5		35.2	.0284
35,000	6.92	−61.0		28.6	.0231
40,000	5.46	−65.5		22.8	.0184
45,000	4.31	−67.0		18.0	.0146
50,000	3.39	−67.0		14.2	.0115
55,000	2.67	−67.0		11.2	.0090
60,000	2.11	−67.0		8.8	.0071
65,000	1.66	−67.0		7.0	.0056

Table 2 (*Continued*)

English Units

Altitude M. S. L. ft.	Pressure in.	Temperature ° F.	Vapor Pressure in.	Density	
				Per Cent Standard	Pounds per Cubic Foot
ANNUAL*					
0	30.03	52.5	0.34	95.9	0.0774
1,000	28.95	50.5	.30	92.9	.0750
2,000	27.91	48.5	.27	89.9	.0726
3,000	26.90	47.0	.23	86.9	.0702
4,000	25.93	45.0	.20	84.2	.0679
5,000	24.98	42.5	.18	81.5	.0658
6,000	24.07	40.5	.16	78.9	.0637
7,000	23.18	38.0	.14	76.4	.0616
8,000	22.33	35.0	.12	74.0	.0597
9,000	21.50	32.5	.11	71.6	.0578
10,000	20.70	29.5	.09	69.4	.0560
12,000	19.16	23.0	.07	65.1	.0526
14,000	17.73	16.5	.05	61.1	.0493
16,000	16.38	10.0	.03	57.3	.0462
18,000	15.12	2.5	.02	53.7	.0434
20,000	13.93	−5.0	.01	50.3	.0406
25,000	11.29	−24.0		42.6	.0344
30,000	9.07	−40.5		35.6	.0287
35,000	7.23	−53.5		29.2	.0236
40,000	5.72	−64.0		23.8	.0192
45,000	4.51	−67.0		18.9	.0152
50,000	3.55	−67.0		14.9	.0120
55,000	2.80	−67.0		11.7	.0095
60,000	2.20	−67.0		9.2	.0074
65,000	1.74	−67.0		7.3	.0059

*The annual means also represent quite closely the average spring and autumn conditions.

"Standard atmosphere." As previously stated, the National Advisory Committee for Aeronautics has adopted, with slight modification, the Toussaint "standard atmosphere" as the standard for altimeter calibration and comparison of aircraft performance in the United States. Toussaint, using as a basis the available data for Europe, proposed the adoption, by all countries, of a "law" of linear decrease of temperature with altitude, starting at a temperature of 15° C. at sea level and attaining −50° C. at an altitude of 10,000 meters. This law is expressed by the equation

$$t = 15 - 0.0065Z,$$

in which

$$t = \text{temperature in } ° \text{ C.},$$

and

$$Z = \text{altitude in meters.}$$

Toussaint further suggested that the application of this law would cease at 11,000 meters, which is approximately the base of the stratosphere. At that level the computed temperature is −56.5° C.

A careful study of all available records showed, both for the United States and Europe, a value of −55° C. as the average annual temperature of the stratosphere. It seemed logical to adopt this, rather than the value at an arbitrary height of 11,000 meters, as the basis for a standard above the region of decrease of temperature with altitude. This action was taken, and the revised standard atmosphere was adopted by all interested government departments.

The basic values and assumptions are as follows:[5]

Sea level pressure, 760 mm. or 29.921 in.

Sea level temperature, 15° C. or 59° F.

Temperature gradient, 0.0065° C./m. or 0.003566° F./ft.

Temperature in stratosphere, −55° C. or −67° F.

The air is a dry, perfect gas.

The altitude at which a constant temperature of −55° C. (−67° F.) begins is 10,769 m. or 35,332 ft.

Values of pressure, temperature and density in the standard atmosphere for selected altitudes are given in Table 3 following.

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[5] For more complete discussions of this subject together with very detailed tables, the reader is referred to National Advisory Committee for Aeronautics Technical Reports Nos. 218 and 246, by W. S. Diehl and W. G. Brombacher, respectively. See also "Aircraft Instruments." by H. N. Eaton and others, and "Engineering Aerodynamics." by W. S. Diehl, Ronald Aeronautic Series.

TABLE 3. STANDARD ATMOSPHERE VALUES AT SELECTED ALTITUDES

METRIC UNITS				ENGLISH UNITS			
Altitude m.	Pressure mm.	Temperature ° C.	Density kg./m.³	Altitude ft.	Pressure in.	Temperature ° F.	Density lb./ft.³
0	760.0	15.0	1.226	0	29.92	59.0	0.0765
500	716.0	11.8	1.168	1,000	28.86	55.4	.0743
1,000	674.1	8.5	1.112	2,000	27.82	51.9	.0721
1,500	634.2	5.2	1.058	3,000	26.81	48.3	.0700
2,000	596.2	2.0	1.007	4,000	25.84	44.7	.0679
3,000	525.8	−4.5	0.909	5,000	24.89	41.2	.0659
4,000	462.3	−11.0	.819	6,000	23.98	37.6	.0640
5,000	405.1	−17.5	.736	7,000	23.09	34.0	.0620
6,000	353.8	−24.0	.660	8,000	22.22	30.5	.0601
8,000	266.9	−37.0	.525	9,000	21.39	26.9	.0583
10,000	198.2	−50.0	.413	10,000	20.58	23.3	.0565
12,000	145.0	−55.0	.309	12,000	19.03	16.2	.0530
14,000	106.0	−55.0	.226	14,000	17.57	9.1	.0497
16,000	77.5	−55.0	.165	16,000	16.21	1.9	.0466
18,000	56.6	−55.0	.121	18,000	14.94	−5.2	.0436
20,000	41.4	−55.0	.088	20,000	13.74	−12.3	.0408
				25,000	11.10	−30.2	.0343
				30,000	8.88	−48.0	.0286
				35,000	7.04	−65.8	.0237
				40,000	5.54	−67.0	.0187
				45,000	4.36	−67.0	.0147
				50,000	3.44	−67.0	.0116
				55,000	2.71	−67.0	.0091
				60,000	2.13	−67.0	.0072
				65,000	1.68	−67.0	.0057

CHAPTER 4

WINDS

Although winds form an integral part of the vertical structure of the atmosphere, they are here treated in a separate section, because of their outstanding importance in aeronautics.

Direction. Owing to the earth's rotation, as explained in Chapter 1, air tends to flow at right angles to the pressure gradient or parallel to the isobars. At and near the surface, however, this tendency is not completely realized, because of friction and viscosity, with the result that air movement makes an angle with the isobars amounting on the average to 20° or 30°. It is much less than this, about 10°, at sea and greatest, sometimes 40° to 50°, in regions much broken up by hills, trees, buildings, etc.

Above the surface the influence of these obstructions rapidly diminishes and the wind direction is on the average very nearly parallel to the isobars at an altitude of about 500 meters (1,600 ft.). At greater heights, owing to the influence of temperature distribution, both vertical and horizontal, the pressure gradients differ widely from those at and near the surface, and the wind direction changes in conformity therewith. It is important to recognize that upper winds are essentially parallel to the isobars[1] *at their own level* and that, in so far as they depart from surface gradient winds, they indicate a pressure distribution that is different from that at the surface.

Turning with altitude. A study of observations with kites and balloons shows that near the surface the turning of

[1] According to definition an **Isobar** is a line joining points at which the barometric pressure is the same either on the average for a stated period or at a specified moment.

TABLE 4. AVERAGE DEVIATION, DEGREES, OF UPPER WINDS FROM SURFACE DIRECTION IN EASTERN AND CENTRAL UNITED STATES

(Plus sign indicates turning to right, minus sign to left)

Surface Direction	Altitude					
	250 m. 800 ft.	500 m. 1,600 ft.	1,000 m. 3,300 ft.	2,000 m. 6,600 ft.	4,000 m. 13,000 ft.	6,000 m. 20,000 ft.
SUMMER						
N	+4	+1	−5	−32	−44	−48
NNE	+17	+17	+9	−17	−82	−92
NE	+11	+15	+9	−24	−70	−110
ENE	+5	+8	+1	−14	−104	−83
E	+9	+14	+21	−3	−4	−12
ESE	+10	+16	+25	+47	+110	
SE	+17	+22	+33	+58	+99	+109
SSE	+10	+19	+26	+48	+102	+136
S	+13	+18	+29	+51	+72	+92
SSW	+8	+17	+27	+38	+69	+46
SW	+8	+13	+22	+30	+58	+42
WSW	+8	+10	+11	+20	+26	+51
W	+3	+2	+3	+7	+10	−1
WNW	+6	+12	+11	+6	+7	+17
NW	+8	+4	−12	−4	+13	−26
NNW	−6	−9	−24	−17	−40	−46
WINTER						
N	+6	+5	−12	−47	−70	−64
NNE	+8	+11	−18	−65	−103	−44
NE	+9	+12	+5	−115	−110	−119
ENE	+13	+23	+78	+104	+106	
E	+23	+50	+95	+151	+187	+182
ESE	+18	+40	+74	+119	+126	+141
SE	+27	+46	+74	+104	+117	+114
SSE	+18	+35	+58	+83	+114	
S	+17	+32	+53	+73	+89	+96
SSW	+16	+27	+43	+59	+76	+108
SW	+15	+25	+39	+50	+58	+71
WSW	+9	+16	+31	+33	+43	
W	+12	+15	+25	+24	+25	+30
WNW	+11	+13	+14	+8	+2	−3
NW	+4	+4	0	−11	−13	−14
NNW	+2	+4	−8	−31	−43	
ANNUAL						
N	+5	+4	−7	−32	−51	−59
NNE	+10	+14	−3	−40	−76	−77
NE	+9	+13	+6	−60	−97	−102
ENE	+10	+15	+22	−56	−118	−125
E	+15	+25	+52	+146	+196	+210
ESE	+12	+26	+46	+88	+135	+160
SE	+19	+31	+51	+79	+116	+110
SSE	+12	+22	+37	+59	+102	+110
S	+13	+22	+36	+60	+77	+95
SSW	+11	+19	+34	+48	+66	+76
SW	+10	+17	+31	+40	+56	+68
WSW	+6	+13	+20	+25	+34	+56
W	+8	+11	+17	+19	+32	+37
WNW	+7	+10	+9	+4	+4	+17
NW	+4	+4	+1	−8	−3	−13
NNW	−1	+2	−6	−18	−31	−31

the winds is generally to the right, clockwise, no matter what the surface direction may be. This turning is most pronounced with southerly surface winds, i.e., east through south to west-southwest, until at 3 to 4 kilometers (10,000 to 13,000 ft.) it amounts on the average to somewhat more than 90°. With northerly winds, on the other hand, i.e., west-northwest through north to northeast or east-northeast, the turning is to the right but small in amount up to about 1 kilometer (3,300 ft.) and then changes to the left, counterclockwise, at higher levels. The deviation is greater in winter than in summer at all stations and is also greater at northern than at southern stations. In other words, the turning is most pronounced when and where the latitudinal temperature gradient is strongest and hence the prevailing westerlies best developed. It is to be noted that in general the amount of the deviation in the upper levels varies directly, or nearly so, as the angle between the surface direction and a westerly direction. For example, a surface southeasterly wind turns more than does a surface southerly wind, both becoming as a rule southwesterly or west-southwesterly in the upper levels. Table 4 gives the average annual turning, in degrees, for the eastern and central United States according to surface wind direction.

The characteristic turning of surface winds is well brought out also in Figure 22.

The percentage frequencies of clockwise and counterclockwise turning are given in Table 5. They show that the tendency to clockwise turning is greater than that to counterclockwise for all directions near the surface but is most pronounced for southerly winds, i.e., east through south to west-southwest; this tendency increases with altitude for these southerly winds and amounts to 80% to 90% at 3 to 4 kilometers (10,000 to 13,000 ft.); with northerly winds the tendency to clockwise turning does not change much with altitude, but the tendency to counterclockwise turning, small near the surface, increases to 60% to 80% at 3 to 4 kilometers (10,000

to 13,000 ft.), the turning is more pronounced, especially near the surface, in winter than in summer and at northern than at southern stations.

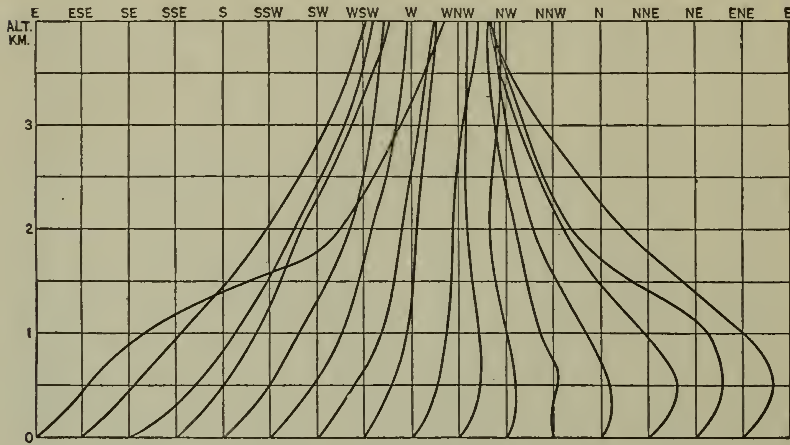

Figure 22. Average Annual Turning of Winds with Altitude in Eastern and Central United States

To convert kilometers to feet, multiply by 3,300.

The frequency of winds from different directions at an altitude of 1 kilometer (about 3,300 ft.) above the surface, in the eastern and central portions of the United States is shown in Figure 23. This brings out, in convincing fashion, the shifting of the winds with height toward a westerly direction. Particularly is this true for the winter season, the only exception being the Florida peninsula. The predominance of a west component increases at higher levels, being largest in winter and in the northern states. For example, at all altitudes between approximately 4 and 10 kilometers (13,000 and 33,000 ft.) the winds in the northern part of the country come from a westerly quarter 90% to 95% of the time in winter, about 80% in summer and 85% to 90% for the year as a whole. In the southern states, a west component is still strongly predominant in winter, but much less pronounced in summer. In the extreme south, that is, Florida and southern Texas, an

Table 5. Average Percentage Frequency of Clockwise (cw.) and Counterclockwise (ccw.) Turning of Winds from Surface Direction in Eastern and Central United States

Surface Direction	Altitude											
	250 m. 800 ft.		500 m. 1,600 ft.		1,000 m. 3,300 ft.		2,000 m. 6,600 ft.		4,000 m. 13,000 ft.		6,000 m. 20,000 ft.	
	cw.	ccw.	cw.	ccw.	cw.	ccw.	cw.	ccw.	cw.	ccw.	cw.	ccw.
SUMMER												
N	37	27	41	34	40	44	31	54	23	69	21	74
NNE	51	11	50	20	45	37	40	51	41	57	43	57
NE	44	20	51	24	50	35	36	54	35	62	24	73
ENE	35	20	43	30	42	38	37	46	37	53	35	63
E	39	22	49	27	54	32	49	36	51	42	49	46
ESE	41	16	51	17	58	23	56	33	56	37	48	51
SE	50	18	56	23	62	24	56	33	60	33	61	35
SSE	45	16	53	21	60	25	66	27	67	22	68	31
S	45	15	57	14	70	17	75	16	77	17	72	22
SSW	38	17	50	16	64	19	69	17	71	17	82	12
SW	40	19	49	20	57	19	65	21	74	20	72	24
WSW	38	20	43	25	50	28	56	27	69	24	67	29
W	34	26	42	31	46	36	58	26	72	21	69	15
WNW	38	16	45	21	46	31	50	33	57	32	83	14
NW	39	25	42	34	40	42	39	42	47	46	43	41
NNW	29	26	32	35	24	56	31	55	17	66	10	79
Means	38	18	47	21	52	26	51	32	52	36	50	42
WINTER												
N	36	24	39	31	30	49	18	73	20	75	19	79
NNE	44	23	49	26	36	46	27	67	14	78	18	67
NE	49	27	55	28	53	39	42	55	35	61	31	65
ENE	47	21	63	21	63	31	56	44	50	48	24	76
E	57	22	68	19	72	24	68	29	59	38	51	49
ESE	62	15	78	12	86	11	88	10	87	15	97	3
SE	65	10	78	7	92	5	89	8	94	6	89	11
SSE	63	8	81	5	91	3	95	4	94	6	75	25
S	54	10	71	6	88	5	96	3	97	3	95	4
SSW	49	8	67	7	84	5	94	2	94	5	91	9
SW	51	15	66	13	80	6	91	4	90	5	97	2
WSW	45	15	55	13	75	7	77	6	80	11	100	0
W	45	12	60	13	73	9	68	10	61	18	74	5
WNW	41	14	48	16	57	17	43	26	34	29	44	33
NW	33	21	36	25	35	31	24	48	23	56	18	48
NNW	31	24	34	28	28	45	9	70	6	91	9	91
Means	45	16	55	16	63	20	58	28	54	35	52	38
ANNUAL												
N	38	25	41	30	34	44	24	62	20	73	18	64
NNE	46	18	49	23	41	41	30	61	22	73	25	71
NE	44	24	51	27	49	37	37	54	31	64	28	68
ENE	44	21	54	24	53	34	46	45	40	55	23	70
E	47	20	56	22	59	29	55	37	54	42	47	51
ESE	49	15	62	16	69	17	70	22	71	25	71	27
SE	56	14	66	15	75	16	74	19	75	22	73	25
SSE	51	13	66	13	74	14	80	16	84	12	79	21
S	47	13	60	12	75	11	84	10	88	9	85	13
SSW	42	14	56	14	71	11	80	9	86	8	86	10
SW	43	21	55	19	67	14	79	12	83	11	86	10
WSW	40	17	51	17	63	17	69	15	76	16	76	20
W	40	18	50	20	58	20	60	17	63	19	74	10
WNW	34	16	42	19	48	23	42	34	38	40	46	25
NW	36	21	40	26	38	29	32	45	30	51	23	56
NNW	31	21	36	27	34	41	21	60	17	73	20	68
Means	41	17	51	19	56	22	55	29	53	36	52	39

east component is more frequent than a west at all levels in summer.

Velocity. Surface friction not only causes the winds to blow across the isobars, but also cuts down their speed to

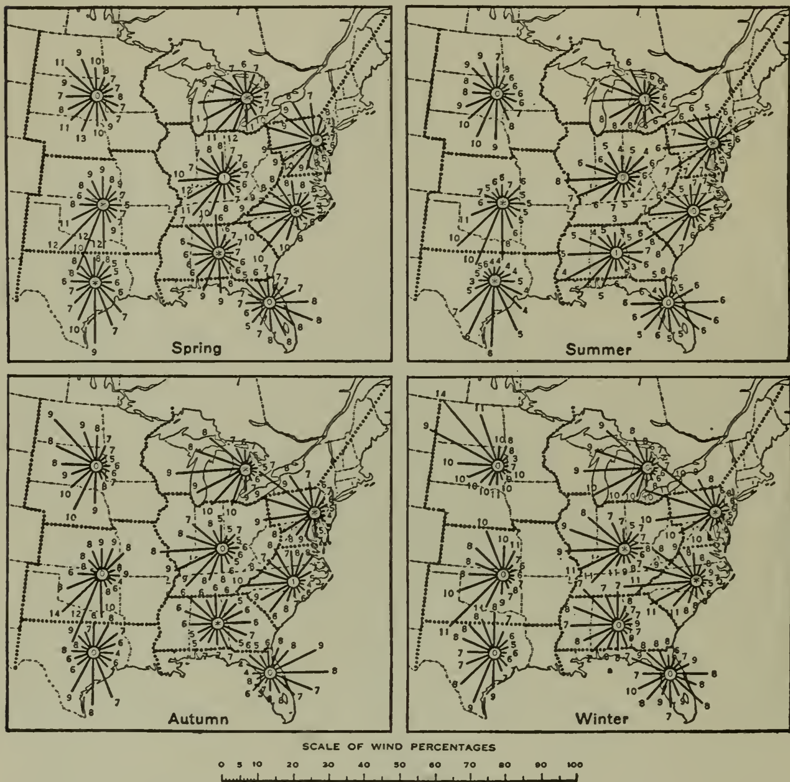

Figure 23. Percentage Frequency and Average Velocity of Different Wind Directions at 1,000 meters (3,300 ft.) Above the Surface in Eastern and Central United States

The figure in the center of each circle gives the percentage of calms; an asterisk (*) denotes less than 0.5 of 1%. The length of the lines, measured by the scale in the lower part of the Figure, represents the frequency of any given direction on the basis of 100. Figures at or near the ends of the lines give the average velocity of those directions. The line north of the circle represents a north wind, and so on.

about half that indicated by the pressure gradient. On the average the gradient velocity (that at which the deflective force due to the earth's rotation and the centrifugal force

jointly balance the horizontal pressure gradient) is attained at an altitude of about 500 meters (1,600 ft.) above the surface. If the pressure gradient is well defined, the corresponding wind velocity, at about 500 meters, can be computed with fair accuracy from well-known equations. These equations all involve the same terms, but differ slightly according to the type of pressure distribution prevailing, i.e., anticyclonic (isobars concentric around high pressure), cyclonic (isobars concentric around low pressure) or straight isobars.

The appropriate equations for these three types are respectively:[2]

$$V = r\,\omega\,\sin\phi - \sqrt{(r\omega\,\sin\phi)^2 - rdP/\rho\,dn}$$

$$V = \sqrt{rdP/\rho\,dn + (r\,\omega\,\sin\phi)^2} - r\,\omega\,\sin\phi$$

and $V = (dP/dn)/2\,\omega\,\rho\,\sin\phi$

in which

V = the velocity in centimeters per second.

r = the radius of curvature of wind path at place of observation, in centimeters.

dP/dn = difference in dynes pressure per square centimeter, per centimeter horizontal distance at right angles to isobar.

ω = angle through which the earth turns per second $= \dfrac{2\pi}{86{,}164}$

ρ = density of the air in grams per cubic centimeter.

$\sin\phi$ = the natural sine of the angle of latitude.

When the pressure gradient is not known, velocities up to 400 or 500 meters (1,300 to 1,600 ft.) above the surface can be determined approximately from the formula

$$\frac{V}{V_0} = \left(\frac{h}{h_0}\right)^{1/5}$$

in which h is the height in meters above the surface for which

[2] The reader who wishes to go into this subject in detail is referred to Humphreys' "Physics of the Air," which contains a fairly exhaustive treatment and includes also tables for readily obtaining the gradient velocity for various conditions of pressure distribution.

the velocity V in meters per second is to be computed, and h_0 the known height (not less than 16 m. or about 50 ft.) at which the velocity V_0 is measured.[3]

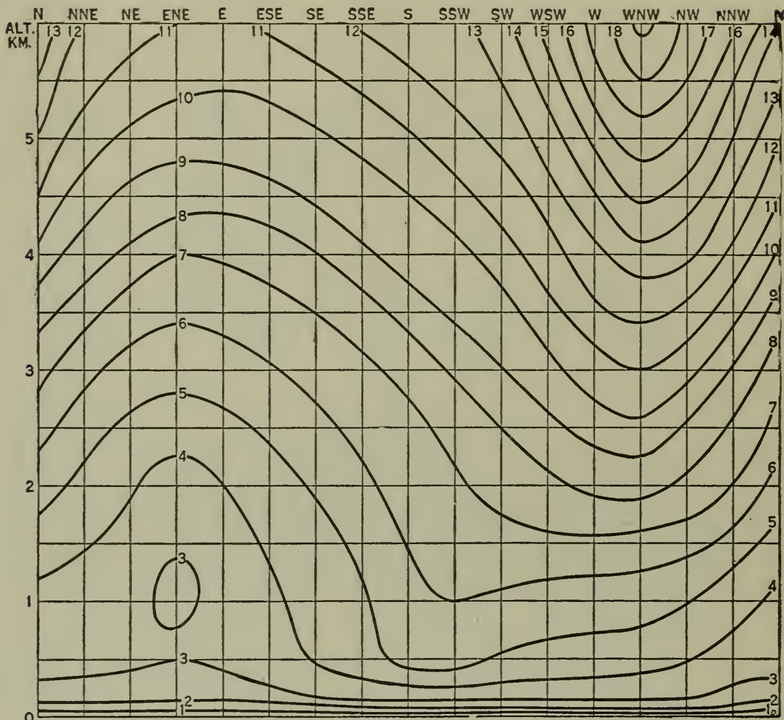

Figure 24. Average Annual Increase of Upper Wind Velocities Above Surface Velocity for Different Surface Directions in Eastern and Central United States

To convert kilometers to feet, multiply by 3,300; m.p.s. to m.p.h., multiply by 2.2.

Change with altitude. The average change of velocity with altitude in the eastern and central United States is shown in Table 6 and Figure 24. From these it is evident that the different directions at the surface are associated with characteristic changes in velocity with altitude quite as definitely as

[3] J. G. Hellman, "Sitz. der K. Preuss. Akad. der Wiss.," 1917, p. 191.

Table 6. Average Increase, m.p.s. and m.p.h. of Upper Wind Velocities Above Surface Velocity in Eastern and Central United States

(The average velocities at different heights may be found by simply adding to the values given in columns 3 to 8 tne average surface velocities in column 2.)

Metric Units

Surface		Altitude, Meters					
Direction	Veloc. m. p. s.	250	500	1,000	2,000	4,000	6,000
SUMMER							
N	3.9	1.9	2.3	2.7	3.8	6.3	9.7
NNE	4.0	2.3	2.4	2.6	2.8	5.9	8.9
NE	3.7	2.0	2.6	2.5	2.7	4.8	7.9
ENE	4.0	2.3	2.6	2.7	2.5	4.4	6.1
E	3.8	1.8	2.2	2.8	2.9	3.6	4.9
ESE	3.9	2.1	2.2	2.0	1.9	2.7	5.1
SE	3.8	2.4	3.1	2.7	2.6	4.2	6.2
SSE	3.9	2.8	3.5	3.1	3.7	3.0	5.9
S	4.2	3.1	4.1	3.7	3.8	5.1	7.1
SSW	4.2	3.2	4.2	3.6	3.5	5.9	6.8
SW	4.1	3.4	3.9	3.7	3.7	5.6	7.2
WSW	3.5	3.3	4.2	3.9	4.6	6.6	11.2
W	3.6	3.1	3.8	4.0	5.3	7.8	8.8
WNW	3.8	3.5	4.4	4.6	5.2	9.0	10.9
NW	3.5	2.5	3.1	3.2	5.6	8.6	13.9
NNW	3.9	2.2	2.8	2.8	4.7	7.0	12.1
Calm	0.0	4.0	5.3	5.6	5.8	8.1	9.2
WINTER							
N	4.8	2.9	3.7	4.6	7.1	14.0	18.7
NNE	4.6	2.8	3.4	3.4	5.0	10.2	17.8
NE	4.3	3.7	3.7	3.6	5.5	11.0	15.7
ENE	4.0	3.0	3.2	3.2	5.1	9.4	
E	3.7	3.2	4.1	4.3	6.1	12.2	16.0
ESE	4.0	3.4	4.8	5.9	6.8	7.9	12.9
SE	4.0	3.6	5.2	6.1	8.0	12.2	
SSE	4.8	4.5	6.4	7.5	9.8	13.1	
S	5.0	4.3	6.2	7.5	9.6	15.1	
SSW	4.9	4.6	6.6	8.9	10.9	14.1	
SW	4.9	4.5	6.4	8.7	11.7	17.1	19.0
WSW	4.7	4.0	6.8	7.6	11.4	19.0	
W	5.5	4.0	5.7	7.7	11.4	18.3	23.3
WNW	5.2	3.5	5.3	7.0	11.3	18.9	
NW	5.8	3.5	4.7	6.7	10.6	17.9	23.7
NNW	5.5	3.2	4.2	6.2	9.5	17.7	
Calm	0.0	4.9	7.1	8.8	11.9	18.0	23.0
ANNUAL							
N	4.8	2.7	3.4	3.7	5.4	9.9	13.8
NNE	4.3	2.7	3.2	3.1	4.3	8.1	11.9
NE	4.1	2.8	3.4	3.2	4.1	8.0	11.7
ENE	4.0	2.8	3.0	2.9	3.4	7.0	11.0
E	3.9	2.5	3.2	3.4	4.1	7.2	10.7
ESE	3.9	2.9	3.6	3.6	4.2	7.6	11.4
SE	4.1	3.2	4.2	4.4	5.1	7.8	11.6
SSE	4.6	3.6	4.6	4.9	5.8	9.0	12.2
S	4.9	3.9	5.5	5.7	6.4	9.5	12.5
SSW	4.8	4.0	5.2	6.0	6.9	9.6	11.9
SW	4.6	3.8	4.9	5.7	7.3	10.6	13.2
WSW	4.5	3.6	4.7	5.3	7.8	11.9	13.2
W	4.6	3.5	4.5	5.5	8.2	12.6	17.4
WNW	4.9	3.4	4.4	5.5	8.4	13.8	19.1
NW	5.0	3.1	4.0	5.0	7.8	13.3	17.6
NNW	5.0	2.9	3.6	4.5	7.0	12.1	16.3
Calm	0.0	4.5	6.0	6.7	8.3	12.8	16.2

Table 6 *(Continued)*

English Units

Surface: Direction	Surface: Veloc. m.p.h.	Altitude, Feet: 800	1,600	3,300	6,600	13,000	20,000
SUMMER							
N	8.7	4.3	5.1	6.0	8.5	14.1	21.7
NNE	8.9	5.1	5.4	5.8	6.3	13.2	19.9
NE	8.3	4.5	5.8	5.6	6.0	10.7	17.7
ENE	8.9	5.1	5.8	6.0	5.6	9.8	13.6
E	8.5	4.0	4.9	6.3	6.5	8.1	11.0
ESE	8.7	4.7	4.9	4.5	4.3	6.0	11.4
SE	8.5	5.4	6.9	6.0	5.8	9.4	13.9
SSE	8.7	6.3	7.8	6.9	8.3	6.7	13.2
S	9.4	6.9	9.2	8.3	8.5	11.4	15.9
SSW	9.4	7.2	9.4	8.1	7.8	13.2	15.2
SW	9.2	7.6	8.7	8.3	8.3	12.5	16.1
WSW	7.8	7.4	9.4	8.7	10.3	14.8	25.1
W	8.1	6.9	8.5	8.9	11.9	17.4	19.7
WNW	8.5	7.8	9.8	10.3	11.6	20.1	24.4
NW	7.8	5.6	6.9	7.2	12.5	19.2	31.1
NNW	8.7	4.9	6.3	6.3	10.5	15.7	27.1
Calm	0.0	8.9	11.9	12.5	13.0	18.1	20.6
WINTER							
N	10.7	6.5	8.3	10.3	15.9	31.3	41.8
NNE	10.3	6.3	7.6	7.6	11.2	22.8	39.8
NE	9.6	6.9	8.3	8.1	12.3	24.6	35.1
ENE	8.9	6.7	7.2	7.2	11.4	21.0	
E	8.3	7.2	9.2	9.6	13.6	27.3	35.8
ESE	8.9	7.6	10.7	13.2	15.2	17.7	28.9
SE	8.9	8.1	11.6	13.6	17.9	27.3	
SSE	10.7	10.1	14.3	16.8	21.9	29.3	
S	11.2	9.6	13.9	16.8	21.5	33.8	
SSW	11.0	10.3	14.8	19.9	24.4	31.5	
SW	11.0	10.1	14.3	19.5	26.2	38.3	42.5
WSW	10.5	8.9	15.2	17.0	25.5	42.5	
W	12.3	8.9	12.8	17.2	25.5	40.9	52.1
WNW	11.6	7.8	11.9	15.7	25.3	42.3	
NW	13.0	7.8	10.5	15.0	23.7	40.0	53.0
NNW	12.3	7.2	9.4	13.9	21.3	39.6	
Calm	0.0	11.0	15.9	19.7	26.6	40.3	51.5
ANNUAL							
N	10.7	6.0	7.6	8.3	12.1	22.1	30.9
NNE	9.6	6.0	7.2	6.9	9.6	18.1	26.6
NE	9.2	6.3	7.6	7.2	9.2	17.9	26.2
ENE	8.9	6.3	6.7	6.5	7.6	15.7	24.6
E	8.7	5.6	7.2	7.6	9.2	16.1	23.9
ESE	8.7	6.5	8.1	8.1	9.4	17.0	25.5
SE	9.2	7.2	9.4	9.8	11.4	17.4	25.9
SSE	10.3	8.1	10.3	11.0	13.0	20.1	27.3
S	11.0	8.7	12.3	12.8	14.3	21.3	28.0
SSW	10.7	8.9	11.6	13.4	15.4	21.5	26.6
SW	10.3	8.5	11.0	12.8	16.3	23.7	29.5
WSW	10.1	8.1	10.5	11.9	17.4	26.6	29.5
W	10.3	7.8	10.1	12.3	18.3	28.2	38.9
WNW	11.0	7.6	9.8	12.3	18.8	30.9	42.7
NW	11.2	6.9	8.9	11.2	17.4	29.8	39.4
NNW	11.2	6.5	8.1	10.1	15.7	27.1	36.5
Calm	0.0	10.1	13.4	15.0	18.6	28.6	36.2

with changes in direction. The principal features disclosed are:

1. From the surface to about 500 meters (1,600 ft.) there is a large increase with all directions; it is greatest with south to southwest winds and least with north-northeast to east winds.

2. At higher levels lowest velocities are still found above easterly surface winds, particularly east-northeast and east; highest velocities, however, occur above west to northwest winds at 2 kilometers (6,600 ft.) and higher, instead of above south to southwest.

3. There is a marked seasonal variation and a less pronounced but still appreciable variation with latitude, the explanation of this being of course the same as that previously given for the variation in deviation from surface direction, viz., the strength of the latitudinal temperature gradient, both at the surface and in the higher levels. This statement applies to the values above easterly winds as well as to those above other directions. It should be borne in mind that easterly surface winds change as a rule to westerly in the higher levels, particularly in winter, and the velocities are of course associated with these westerly directions. In the few cases in which the easterly surface winds remain easterly with increasing altitude the velocities are as a rule comparatively low.

Annual variation. The characteristic seasonal change in upper wind velocities is well shown in Figure 25.[4] It is to be noted that the variation at and close to the surface is very slight, in striking contrast to that above the "gradient wind" level, about 500 meters (1,600 ft.). Similar charts for more northern stations would show the same general features, with, however, somewhat higher velocities in summer.

Diurnal variation. As is well known, wind velocity at the surface is higher during the day than at night. The max-

[4] J. A. Riley, "The Winds in Oklahoma and East Texas," *Monthly Weather Review*, Vol. 51, pp. 448-455, September, 1923.

imum occurs on the average between noon and 3 P.M. and the minimum between midnight and 6 A.M. It is not so well known, but should be clearly recognized, that the daily march at upper levels is the exact opposite of this, as shown in Figure 26. It is to be noted that the variation characteristic of the

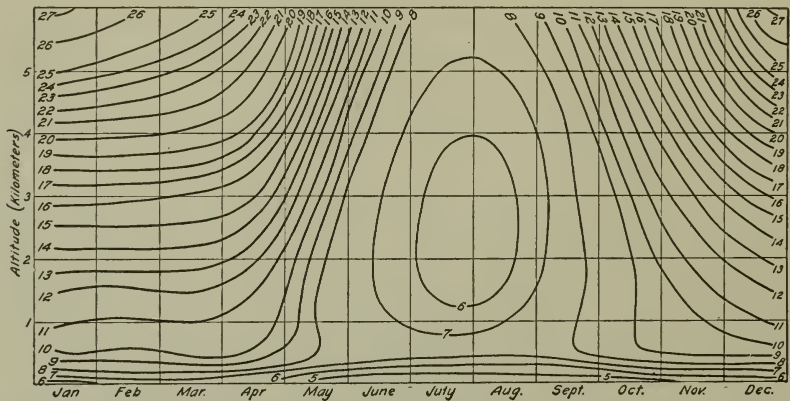

Figure 25. Average Upper Wind Velocities, for all Directions, in Oklahoma and East Texas (after Riley)

To convert kilometers to feet, multiply by 3,300; m.p.s. to m.p.h., multiply by 2.2.

surface extends only to about 100 meters (330 ft.) and that it amounts on the average to about 2 meters per second (4 m.p.h.) whereas that at higher levels is 3 or 4 meters per second (7 to 9 m.p.h.). It is largest between 400 and 600 meters (1,300 and 2,000 ft.) above the surface.

Other features of special interest are the comparative absence of the sharp increase in velocity with height in the afternoon that is so characteristic of other periods of the day and of all portions of the night; the virtual disappearance of a diurnal variation at 1 to 1½ kilometers (3,300 to 4,900 ft.); and the marked contrast between continental and marine conditions, as represented by the Drexel and Key West graphs respectively. At Key West, which is far removed from any extended land areas and relatively free therefore from appreciable convectional activity, the diurnal range, both at the

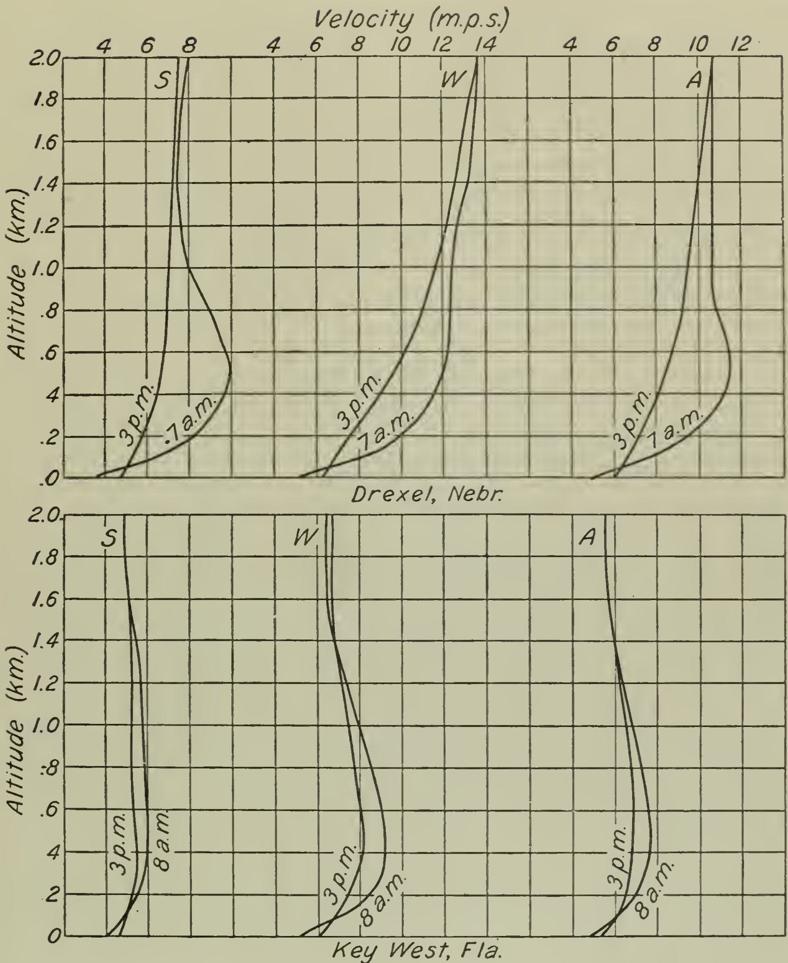

Figure 26. Average A.M. and P.M. Wind Velocities at Drexel (near Omaha), Neb., and Key West, Fla.

S=summer; *W*=winter; *A*=annual. To convert kilometers to feet, multiply by 3,300; m.p.s. to m.p.h., multiply by 2.2.

surface and above, is very small, and ceases altogether at about 1,400 meters (4,600 ft.). Moreover, near the surface the change with altitude in the afternoon is similar to that in the morning, though less pronounced, whereas at Drexel and pre-

sumably at continental stations in general, the character of the A.M. and P.M. curves is distinctly different.

Average directions and velocities. The characteristic turning of winds with altitude and the increase in velocity above surface values for different directions at the surface are presented in Tables 4 and 6, and have already been discussed. The actual average directions and velocities for the eastern and central portions of the United States can be readily obtained by combining the values in these two tables.

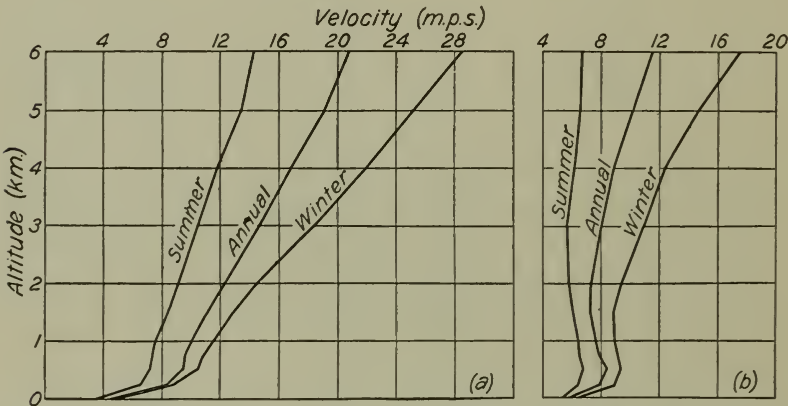

Figure 27. Average Summer, Winter, and Annual Upper Wind Velocities
(a) Northern states (Lake region); (b) southern states (Florida peninsula). To convert kilometers to feet, multiply by 3,300; m.p.s. to m.p.h., multiply by 2.2.

In Figure 27 are presented the summer, winter, and annual velocities, based on observations at two groups of stations—one in the Lake region and the other in the Florida peninsula. These, although showing the marked variation, in actual values, with latitude, are characteristic of average conditions throughout the temperate zones. The chief features are: (a) a marked increase from the surface to the level of gradient winds, about 500 meters (1,600 ft.); (b) little change, often a decrease, from that level to about 1,500 meters (4,900 ft.); and (c) a gradual increase from the latter to the base of the stratosphere.

The increase from the surface to the gradient wind level is of the order of 100%, i.e., on the average the velocity at 500 meters (1,600 ft.) is about double that at the surface. In individual cases it is frequently very much greater than this, particularly at night and in winter. On the other hand, in the middle of the day, when convection is active, and in summer, when horizontal temperature gradients are weak, the increase is slight, though usually present in some degree.

Velocities in the region between 500 and 1,500 meters (1,600 and 4,900 ft.), approximately, are exceedingly irregular. There is frequently a decrease, more or less pronounced, to a minimum near the 1-kilometer (3,300 ft.) level. Such decrease occurs when there is a marked change in wind direction with height; also, along the border line between an anticyclone and a cyclone. On the other hand, if horizontal pressure and temperature gradients at the surface are in the same direction and strong, or even if the temperature gradient is strong and there is no well-marked pressure gradient at the surface, the wind velocity usually increases above 500 meters (1,600 ft.), though less markedly than below that level. This latter condition occurs most frequently in winter; in fact, predominates then to the extent that the rate of increase between 500 and 1,500 meters (1,600 and 4,900 ft.) is on the average about the same as at higher levels. In summer and to a less extent in spring and autumn, pressure and temperature gradients are frequently ill defined, with resulting irregularities in the winds at moderate levels. Even in these seasons, however, there are occasions when the velocity increases considerably with altitude. The average of all conditions then is one of little change with altitude at these levels at northern stations and a small decrease at southern. The curves show a quite regular rate of change with altitude between about 500 and 1,500 meters (1,600 and 4,900 ft.) owing to the smoothing which results from averaging numerous individual observations in which the changes usually are abrupt and often are

large and occur at slightly different altitudes from day to day. It seems likely that the general average, if over a long period, approaches the type of change of velocity with height that would obtain normally if there were no cyclonic, anticyclonic, or other disturbances, except turbulence, in the flow of the air, while the great majority of individual observations show the effects of some one or more disturbances of this nature.

Above 1,500 meters (4,900 ft.) there is, in general, a fairly steady increase in velocity with height in conformity with the poleward temperature gradient that prevails at those levels. At southern stations, this increase is very small in summer owing to the frequency with which stagnant conditions of pressure and temperature prevail. Not infrequently the observations show practically no wind at all heights reached, during this season.

Turbulence.[5] "Bumps," "bumpy air," "holes in the air," and "air pockets" are now common parlance among fliers and, to a lesser but increasing extent, among the general public also. "Turbulence" and "gustiness" are the more formal, but less expressive, terms for conditions that every pilot sooner or later experiences and which at times provide a severe test for his skill in preventing disaster. A feature that at first strikes one as singular is that bumps and so-called "holes in the air" occur under a great variety of weather conditions. They are found on clear days and on cloudy days; when winds are light and when they are strong; at night and during the daytime; and over both land and water surfaces. Notwithstanding this, their cause may in all cases be traced to one or

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[5] References: Wm. R. Blair, "Meteorology and Aeronautics," Report No. 13, National Advisory Committee for Aeronautics, 1917. T. R. Reed, "Some Meteorological Observations of a Bombing Plane in France," *Monthly Weather Review*, Vol. 48, pp. 216-217, April, 1920. C. L. Meisinger, "Free Balloon Flight in Northeast Quadrant of an Intense Cyclone," *Monthly Weather Review*, Vol. 47, pp. 231-233, April, 1919. C. L. Meisinger, "Balloon Race from Fort Omaha through Thunderstorms," *Monthly Weather Review*, Vol. 47, pp. 533-534, August, 1919. C. F. Brooks, and others, "Effects of Winds and Other Weather Conditions on the Flight of Airplanes," *Monthly Weather Review*, Vol. 47, pp. 523-532, August, 1919. A. Peppler, "Über vertikale Luftbewegungen." *Deutsche Luftfahrer Zeitschrift*, Berlin, 17, Jahrgang, November, 1913, pp. 578-580. A. Friedmann and J. Tamarkin, "Über eine Methode der Bestimmung der Vertikalen Windgeschwindigkeit," *Meteorologische Zeitschrift*, Braunschweig, Band 41, März, 1924, pp. 90-91. F. Entwistle, "Wind Structure in Relation to Air Navigation," *Journal Institute of Aeronautical Engineers*, Vol. 1, No. 3, pp. 5-18, March, 1929, London.

the other of two atmospheric conditions: first, changes in the horizontal movement of the air in which the aircraft is flying: and second, vertical movements in the air.

Mechanical turbulence. The first condition is usually referred to as "gustiness" and consists of a succession of comparatively rapid fluctuations in the velocity of the wind. Special instruments have been designed for measuring gustiness and these show that the range from the lull to the peak in a moderate to high wind, 15 to 40 miles per hour (7 to 18

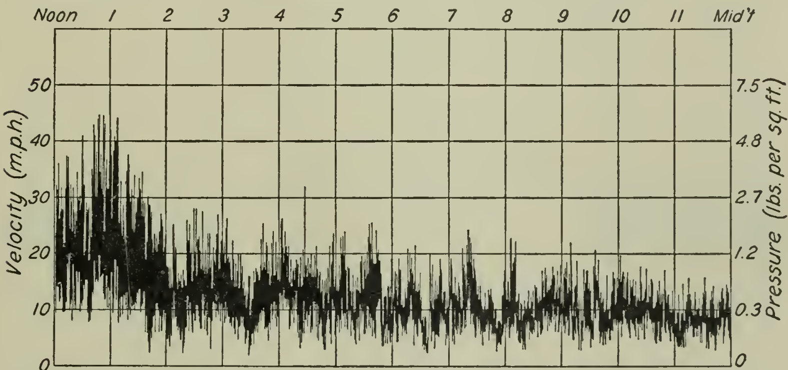

Figure 28. Record of Fluctuations in Wind Velocity on a Gusty Day at Washington, D. C.

To convert m.p.h. to m.p.s., multiply by 0.45; lb./sq.ft. to kg./sq.m., multiply by 4.88.

m.p.s.), is anywhere from 25% to somewhat more than 100% of the average velocity. A 100% variation, which means for example that a wind averaging 30 miles per hour (13 m.p.s.) fluctuates between 15 and 45 miles per hour (7 to 20 m.p.s.), is by no means uncommon. Figure 28 is a reproduction of a record obtained with a pressure-tube anemometer. As indicated, the average velocity diminished from about 20 to 10 miles per hour (9 to 4.5 m.p.s.), but the individual fluctuations ranged between 45 and 3 miles per hour (20 and 1 m.p.s.).

These fluctuations are largest and most frequent near the earth's surface, and in fact gustiness owes its existence in large part to the irregularities of the terrain over which the

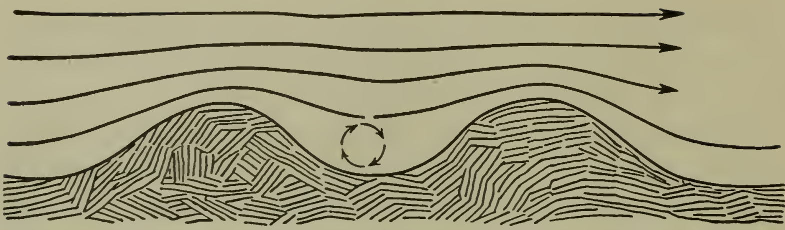

Figure 29. The Flow of Air Over Two Ridges (after Dr. Franz Linke). (Note eddy in valley to leeward of ridge at left.)

air is moving, or to obstructions such as buildings, small patches of woods, etc., where a strong wind blows over comparatively quiet air. (See Figures 29, 30, and 31.)

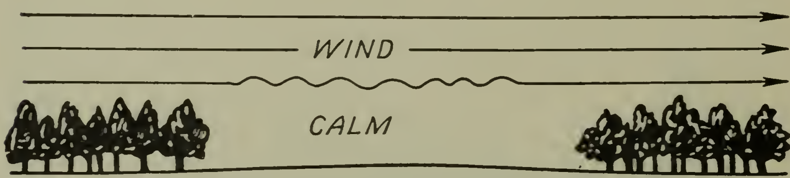

Figure 30. Gustiness Caused by Groups of Trees (after Linke). (The air waves formed between the moving air above and the quiet air below may be troublesome.)

Over land that is relatively level, appreciable gustiness does not ordinarily extend above 500 feet (150 m.). On the other hand, in very rough country, especially with a high wind, con-

Figure 31. Eddies Produced by Buildings. (The waves are made visible by smoke.)

siderable bumpiness from this source is at times experienced up to 2,000 or 3,000 feet (600 to 900 m.) and even higher in the case of wind blowing over a mountain ridge.

Fluctuations in the horizontal movement of the air, such as we have been describing, temporarily alter the speed of the aircraft with reference to the air and result in an upthrust or a downthrust, unless prompt adjustment of the controls is made. For example, suppose that a machine is flying in the same direction as the wind and is maintaining a constant level; if now, the wind velocity suddenly increases, the speed of the machine *relative* to the air in which it is flying is lessened and the machine drops as if it had encountered an actual "hole in the air." If, on the other hand, the wind velocity suddenly diminishes, then the speed of the machine relative to the air increases and there is an upthrust or what is commonly called a "bump."

Conversely, if a machine is flying against the wind, an increase in the velocity of that wind causes, until adjustment can be made, a temporary increase in the relative speed of the machine, resulting in a bump, whereas a decrease in wind velocity produces also a decrease in the relative speed of the machine and therefore a sudden drop.

Similar effects are experienced when the aircraft is changing its level and successively passes into layers of air having different velocity or direction or both. It is rare that uniform direction and velocity of the wind are found throughout any considerable range of altitude. In other words, the normal state of the atmosphere, particularly in the lower levels, is one of rather marked stratification, layers of low velocity alternating with those of comparatively high velocity, often with a change in direction, the transition being as a rule quite abrupt. When a machine is passing from one of these layers to another, its speed relative to the air is temporarily increased if flight is with the wind and the latter decreases or if against

the wind and the latter increases, and temporarily decreased if the opposite sequence of events occurs.

Thus far we have considered bumpiness associated with horizontal movements of the air. The fluctuations in these movements as a rule are mechanically produced, that is, they result from friction with the earth's surface and to a lesser extent from friction between adjoining layers of air. There is more or less vertical movement accompanying these changes, but as a rule it is of minor importance, except at the surface near buildings or in the vicinity of hills, mountains and other obstructions. Thus a wind blowing across a mountain ridge has a strong upward component on the windward side of the mountain—a condition that was very helpful to Lieut. Macready in his non-stop flight across the country, as the following excerpt from his report shows:[6]

"As the country around Tucson was approached, it became a continuous struggle, with the climb at practically the absolute ceiling of the airplane, in order to cross over the high passes, mountains, and elevations, the passing of each obstacle being doubtful.

"The atmosphere was very rough and bumpy, with numerous air currents, which would raise the airplane 100 feet (30 m.) or more at a time, sometimes possibly 200 or 300 feet (60 to 90 m.) and then let it down quickly, even though the same position or angle of climb of the machine was maintained. Many times it seemed that the T-2 would not be able to get over these high areas, but, apparently just as the summit was reached, one of the air currents coming over the high elevation would raise the airplane just enough to clear the top." Apparently this process was assisted by a return eddy near the surface, blowing up the mountain on the leeward side.

In some cases the turbulence in the form of vertical currents associated with very rugged country, especially canyons

[6] Lieut. John A. Macready, "The Non-Stop Flight Across America," *National Geographic Magazine*, July, 1924, p. 33.

and jagged mountains, is exceedingly troublesome. An interesting observation along this line has been reported by B. M. Varney,[7] who watched with powerful binoculars, and sketched a 7-minute flight of a flat disc of paper which he had released

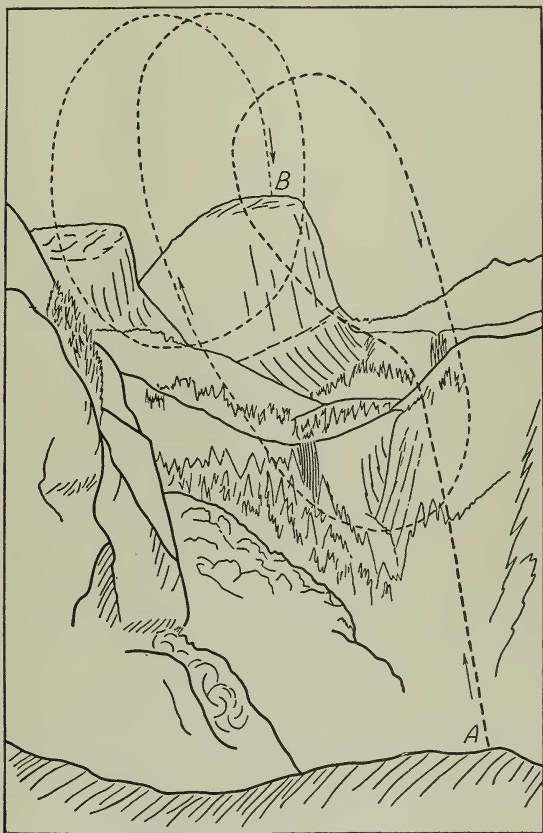

Figure 32. Path of Flight of Paper Disc, Observed from Sierra Point, Yosemite National Park, Early Afternoon of June 8, 1920, Looking East

North side of canyon of Merced River on left. Vernal Falls in middle distance, 1/4 mile (0.4 km.) away. West face of Mt. Broderick, left distance, 9/10 mile (1-1/2 km.). Nevada Falls (right), 1-1/10 miles (1.8 km.). Summit of Liberty Cap, 1-1/10 miles (1.8 km.). The top of the first turn in the spiral, estimated to be about 500 feet (150 m.) above point of observation; top of last turn, over Liberty Cap, estimated at about 2,500 to 3,000 feet (750 to 900 m.), the latter estimate being based on the fact that the summit of Liberty Cap is 1,600 feet (500 m.) above Sierra Point, and that the face of the sheer cliff extends about 1,300 feet (400 m.) below the summit.

[7] B. M. Varney, "Daytime Wind Turbulence in a Mountain Valley," *Monthly Weather Review*, Vol. 48, pp. 336-337, June, 1920.

on the brink of a cliff about 1,100 feet (340 m.) above the floor of Yosemite valley. The sketch is shown in Figure 32. The distance from A to B is somewhat more than a mile (about 1.6 km.).

Buildings and topographic irregularities produce eddies and gusts, their influence extending to a considerable height, on the average about four times that of the obstructions themselves above the general level of the earth's surface in their vicinity. In addition, there is the danger from turbulence in the lee of obstructions. Major Blair has cited a case of this kind.[8] The obstruction was a small circular building, kite reel shelter, about 18 feet (5½ m.) in diameter and 20 feet (6 m.) high, set in a cleared space on which snow had recently fallen. (See Plate XXIII.) A wind of about 50 miles per hour (22 m.p.s.) was blowing. On the leeward side of this building "the ground was kept bare of snow for a width of about 10 feet (3 m.) and a distance of 525 feet (160 m.); at this point the surface took a decided downward slope. As the air current passed the tower two helices were formed. To one standing in the tower the rotation of the air in the helix on his left was clockwise; on his right counterclockwise, as shown by the suspended snow. The air descending in the middle of the path swept the snow outward and forward to both sides."

Thermal turbulence. The principal cause of vertical movements which are so troublesome to flyers is difference in density of adjacent masses of air, resulting for the most part from differences in temperature. These differences in temperature are brought about in various ways, but can, of course, all be traced back ultimately to variations in the heat received from the sun. Thus, on the average and in general, a south wind is warmer and therefore less dense than a north wind, and when the two meet, the colder air forces up the

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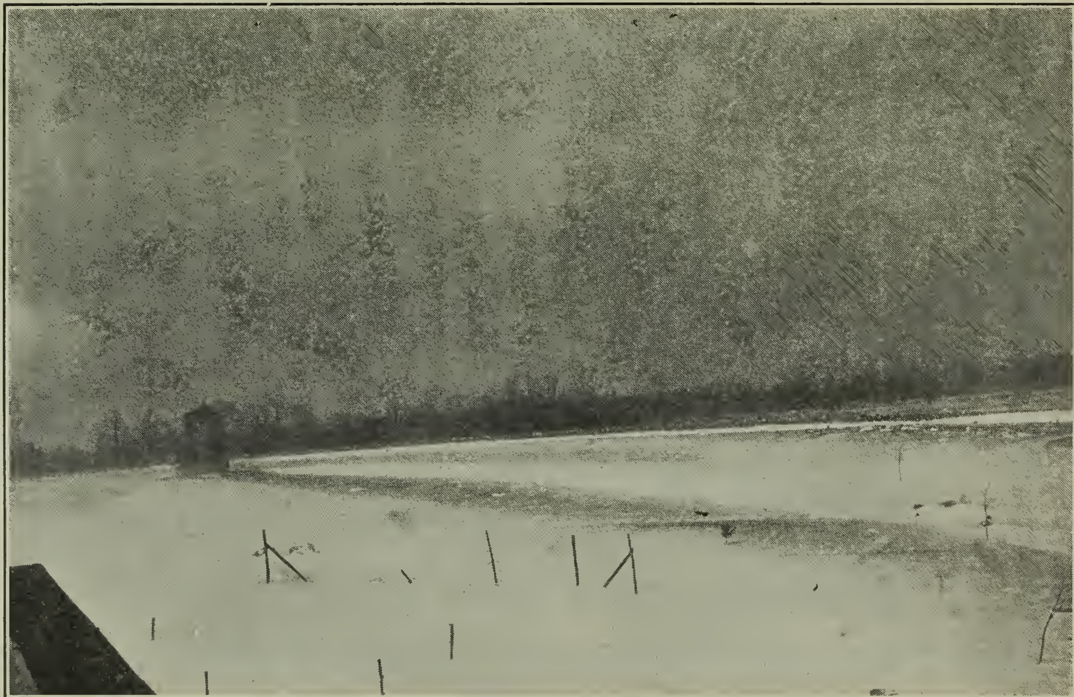
[8] W. R. Blair, "Meteorology and Aeronautics," Report No. 13, National Advisory Committee for Aeronautics, 1917.



Mount Weather, Va. Wm. R. Blair

Plate XXIII. Disturbance Caused to Leeward of a Small Round Tower During a High Wind

warmer. If the difference in density is considerable, as in thunderstorms and along the so-called squall line which latter usually extends southwestward from the center of low-pressure areas or "cyclones" then vertical movements are likely to be and often are violent and exceedingly irregular.

A more common, and therefore in many respects a more important class of vertical movements, is that resulting from local and temporary variations in air density. The principal source of these variations is the variable absorptive power of the surface upon which the sun's rays fall. It is well known that local heating is more intense over land than over water surfaces, but over land itself there is also wide variation. Thus black soil becomes hotter than light, a ploughed field than a meadow, and dark colored vegetation than light colored. In addition, the exposure of the surface has a bearing in this connection. A small area inclosed by buildings or trees, thus protecting it from whatever wind there may be, is unduly heated, and the southern side of a hill or ridge becomes hotter than the northern side. Finally, when the sky is partly cloudy, particularly if the clouds are of the cumulus type, the sun's rays pass between the clouds and heat small areas upon which they fall, while adjoining regions are in the clouds' shadow and are therefore not heated.

Whatever the cause of the variations in temperature of adjacent air masses, the results are the same. The warmer, therefore lighter, air is forced by the colder, denser air to rise, the ascent continuing until by adiabatic cooling the air has the same temperature and density as the air surrounding it. The rate of ascent and the height to which the air rises are proportional to the difference in the temperatures of the two masses. In the early morning there is considerable turbulence from this source, but it is confined to the lowest levels. As the day advances, the thickness of the disturbed layer increases, reaching a maximum about 2 to 4 P.M. This maximum thickness is very variable, but on clear days it averages about

3,000 to 4,000 feet (900 to 1,200 m.) in summer, and about 2,000 to 3,000 feet (600 to 900 m.) in winter. The rate of ascent of the air during these conditions also varies considerably, but seldom exceeds 12 to 15 miles per hour (5 to 7 m.p.s.), except in thunderstorms. Observations with pilot balloons show that vertical movements of 5 to 10 miles per hour (2.2 to 4.5 m.p.s.) are not uncommon. When they occur, unless the atmosphere is abnormally dry, they are frequently followed by the development of thunderstorms, in which of course the movements are much more violent, certainly 18 to 20 miles per hour (8 to 9 m.p.s.) when hail is formed and probably at times as high as 80 or 100 miles per hour (35 to 45 m.p.s.). (See Chapter 8.) Experience and observation both show that ascending currents are more pronounced than descending. Naturally, for any air that goes up an equivalent amount must come down, but it appears that the descent takes place more slowly and over a greater area. However, descending currents of 6 to 8 miles per hour (2.5 to 3.5 m.p.s.) have been measured.

The effects produced on aircraft by these vertical currents are similar to those resulting from fluctuations in the speed of air that is moving horizontally. A machine that passes from still air (in a vertical sense) to an ascending current receives an upthrust or bump just as it does when flying against a wind whose speed suddenly increases. Conversely, when passing from an ascending current to air that is still or that has a downward component, the machine loses in part its support and drops as though it had encountered a "hole in the air."

Thus far we have discussed bumpiness as it affects a machine when the latter passes as a whole from one condition of the air to another. Actually, it is frequently the case that only a part of the machine is affected by the new condition. Thus, one wing may be in rising and the other in still or descending air, and a decided tilting of the machine results.

Under these conditions considerable skill is required in maintaining an even keel.

The flyer soon learns from experience under what conditions he may expect to encounter bumpiness. He avoids flying very low when passing from heated land to a lake or other body of water. He is not surprised to find a bump when he crosses a highway, a railroad or a shoreline on a hot day. If he is wise, he keeps a considerable distance between himself and a thunderstorm, particularly in the vicinity of the squall wind at its front. The danger here lies not so much in the initial ascending current which merely carries the aircraft up, as in the descending current just behind it which causes the craft to drop, as if without support, and to crash if flying low. He knows also that he will, in general, find much smoother flying above cloud layers than below them; at night than in the daytime; over water than over land surfaces; and in level regions than in mountainous country. He learns, often from experience, that flight above forest or other fires should be avoided, and that hot afternoons, particularly in southern states, are troublesome. In short, he becomes, in a very real sense, airwise and is ready for each situation the instant that it confronts him.

The novice, as in all other endeavors but more critically in this one, is of course handicapped, and he is fortunate if he is not confronted with a seriously disturbed condition of the air before he has met and learned to overcome the effects of comparatively mild bumpiness. His tendency at first, a perfectly natural one, is to overcontrol in his effort to correct for sudden changes. With experience he finds it possible and also wise for the most part to let the machine ride out the irregularities, for he finds in many instances that an upthrust is followed by a downthrust, and when he has passed both, the level has not been greatly changed. Near the surface, particularly in taking off and in landing, even small inequalities in air structure are troublesome and the pilot must use his

controls carefully. At greater heights they do not bother him appreciably, when small; and when they are large, he has sufficient space in which to maneuver, except in the case of particularly violent turbulence such as occurs in thunderstorms and line squalls. He should, of course, always keep a respectful distance from these latter dangerous conditions.

Further discussions of turbulence will be found in the Chapters on "Thunderstorms" and "Airship Meteorology."

Soaring flight.[9] Much has been written concerning some special form of energy imparted by the sun to the air whereby sustained flight is accomplished by birds without flapping their wings. This idea has been definitely abandoned in the light of critical analysis which is supported by numerous observations.

Soaring flight is impossible in still air or in a perfectly steady, horizontal wind. The latter is an aid in getting a glider off the ground, by pointing *into* the wind, and in increasing the distance covered, by pointing *with* the wind, but is of no assistance, by any maneuvering whatsoever, in maintaining a glider at a constant level or enabling it to rise.

If, however, a horizontal wind is rapidly fluctuating, or gusty, as is usually the case, at any rate near the earth's surface, energy can be derived from it by pointing into the wind as it increases in velocity and with the wind as it decreases. Birds undoubtedly do this successfully but as yet man-made machines cannot maneuver with sufficient rapidity to benefit from these "internal accelerations" in the wind. In addition, they are very rarely large enough to sustain a glider for more than a very brief period.

Soaring flight is assisted also when the wind is strongly

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[9] References: Gilbert T. Walker, "Meteorology and the Non-Flapping Flight of Tropical Birds," *Proceedings of the Cambridge Philosophical Society,* Vol. XXI, Part IV, pp. 363–375, 1923. S. Broditsky, "Motorless or Wind Flight," *Nature,* Vol. 110, No. 2762, pp. 483–485, October 7, 1922. Wolfgang Klemperer, "Soaring Flight," *Journal of the Franklin Institute,* Vol. 204, No. 3, pp. 293–327, September, 1927. F. Entwistle, "The Royal Aero Club Gliding Competition, October 16–21, 1922," *The Meteorological Magazine,* Vol. 57, No. 682, pp. 263–266, November, 1922. A. F. Zahm, "Soaring Flight," *The Journal of the Maryland Academy of Sciences,* Vol. 1, No. 1, pp. 8–19, January, 1930.

stratified, layers of decidedly different velocities being in close contact one with the other. Moreover, birds find it possible to take advantage of rapid pulsations in direction. Here again the changes are so rapid that the maneuvering of a large, relatively clumsy and unwieldy machine is too difficult to derive much benefit from them. It is not to be overlooked that the bird has instantaneous control of all its bodily actions, enabling it to adjust wings, tail, individual feathers, legs and head in such fashion as to derive the utmost assistance from every sudden change in the wind. No matter how well a pilot knows his machine and its capabilities, it never becomes a part of him.

It seems reasonably certain that the only condition really favorable to soaring flight is that in which the air has upward component of motion. This may be either thermally or mechanically produced. Soaring of birds is most widespread and successful in the tropics and in the warmer portions of the temperate zones, where convection is most pronounced. It is carried on at great heights. Man-made gliders also have made some very good flights by utilizing the more vigorous heat-produced rising currents in the vicinity of cumulus clouds and, in one or two cases, in a thunderstorm. Needless to say, such attempts are beset with hazard and should not be made.

A good illustration of mechanically produced upward movement of air is found just above the waves of the sea, where some birds, notably the albatross, are enabled to soar for hour after hour without apparent movement of their wings. This source of energy is not sufficient and is too close to the surface to be utilized by man-made gliders.

Thus far the one condition most favorable for the soaring efforts of man is that in which a fairly strong, steady wind blows at right angles to a straight or slightly concave ridge. To be successful it is necessary that the wind be strong enough or the ridge sufficiently steep, or both, so that the resulting upward current shall equal or exceed the slowest rate of fall

of the machine when gliding in perfectly still air. The necessary velocity of this upward current will of course depend on the weight and gliding efficiency of the machine. In many cases skilful pilots have been able to stay aloft for several hours and to make flights of nearly 100 miles (160 km.) in length.

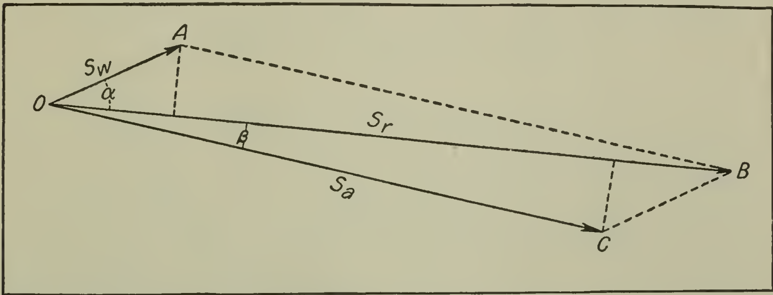

Figure 33. Diagram Showing Resultant Course and Speed of an Aircraft Under the Combined Action of Its Own Direction and Speed and Those of the Wind

The use of winds in plotting a course. In order to determine, under given conditions of wind, the direction toward which an airplane should be headed in order that it may keep to any desired course, and the resultant speed along that course, it is only necessary to resort to that elementary principle of mechanics, applicable to any body moving through a medium which itself is in motion, viz., the principle of the composition of speeds. For example, in Figure 33 let OB represent a course which a pilot desires to follow and OA or S_w the speed of the wind, this wind making an angle α with the line OB.

Also, let S_a represent the air speed (i.e., speed in still air) of the airplane.

The angle β which the airplane should make with OB, in order that the latter shall be the resultant course, may be readily computed, since the sines of the two angles are inversely proportional to the two speeds, or

$$\sin \beta = \frac{S_w \sin \alpha}{S_a}.$$

Also, by completing the parallelogram, we find graphically the resultant speed, or $S_r = S_w \cos \alpha + S_a \cos \beta$.

To take a typical case, suppose the desired course is E 5° S; wind bearing and speed are E 25° N, 10 meters per second (about 22 m.p.h.); and the air speed of the machine is 40 meters per second (about 90 m.p.h.). Then $\alpha = 30°$.

$$\sin \beta = \frac{10 \times \sin 30°}{40} = 0.1250$$

$$\beta = 7°, \text{ or } OC = \text{E } 12° \text{ S}$$

$$\text{Also } S_r = 10 \times \cos 30° + 40 \times \cos 7°$$

$$= 48 \text{ m.p.s., or about } 107 \text{ m.p.h.}$$

From the foregoing brief discussion, it is evident that, with an airplane of known air speed, the successive directions toward which the machine should be headed and the total distance covered in a given time (or the time required to fly over a given course) are quickly and easily determined, providing the prevailing wind conditions are known. These conditions, as previously stated, are determined from actual observations with pilot balloons; or in the absence of such observations, by means of equations for computing the gradient wind from the weather map.

Wind factor in flight. In fixing regular flying schedules between two points, it is essential to know: (a) the wind factor or resultant wind for which allowance must be made; and (b) the frequency of head or cross winds of different speeds along the course that will reduce the ground speed. There are two ways in which these values can be determined: (1) from actual upper air observations with kites and balloons or other means; and (2) from the records of a regular flying service that has been in operation for at least a year. Both of these methods have been employed in a study of conditions between New

York and Chicago and have been found to agree closely.[10] The results of this study show that at ordinary flying levels the wind factor is about 7.5 miles per hour (3.5 m.p.s.). By "ordinary flying levels" is meant 1,000 to 5,000 feet (300 to 1,500 m.). The altitude of flight of the Air Mail planes

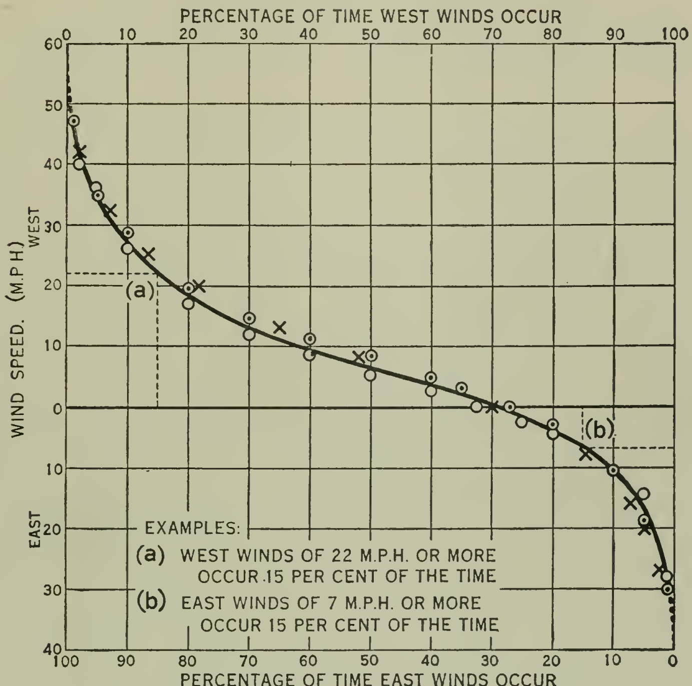

Figure 34. Annual Percentage Occurrence of East and West Component Winds of Different Velocities at Ordinary Flying Levels along the New York-Chicago Airway

The crosses are based on kite and balloon observations; open circles on westbound Air Mail flights; and circles with a dot, on eastbound flights. To convert m.p.h. to m.p.s., multiply by 0.45.

varied according to the weather and wind conditions prevailing, but, fortunately for our present purpose, the wind velocity does not greatly change on the average within the altitude

[10] W. R. Gregg, and Lieut. J. P., Van Zandt, "The Wind Factor in Flight: An Analysis of One Year's Record of the Air Mail," *Monthly Weather Review*, Vol. 51, pp. 111-125, March, 1923; and "The Frequency of Winds of Different Speeds at Flying Levels between New York and Chicago: A Further Analysis of the Records of the Air Mail Service," *Monthly Weather Review*, Vol. 52, pp. 153-157, March, 1924.

limits above given, as indicated in Figure 27. The data from these flights and from kite and balloon observations also made possible the determination of the frequency of opposing winds of various speeds. There were included not only the head winds but also the equivalent component effect of cross winds. The frequencies thus determined are shown in Figure 34.

With these frequencies it is possible to fix schedules for aircraft of different cruising speeds that can be guaranteed

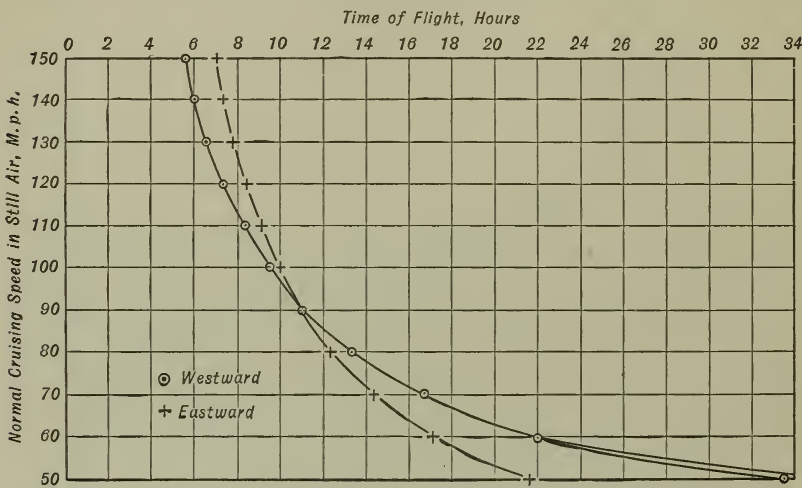

Figure 35. Curves Showing Schedules for Westward and Eastward Flight Between New York and Chicago, 770 miles (1,240 km.), that can be Guaranteed 90% of the Time for Aircraft of Different Cruising Speeds

Allowance made for unfavorable weather conditions; head and cross winds; 1-hour service stops each way; and change of time. To convert m.p.h. to m.p.s., multiply by 0.45.

any desired percentage of the time so far as winds are concerned. Such schedules are given in Figure 35 on the basis of a 90% guarantee, allowance being made for failures 5% of the time on account of opposing winds and 5% because of other unfavorable conditions, such as severe rain or snow storms, poor visibility, etc. Allowance is also made for 1-hour service stops each way and for the difference in time, i.e., the times shown are those by the clock in the two cities, not actual elapsed time.

The importance of the close agreement between the Air Mail records and the kite and balloon data lies in the fact that either can be used, when both are not available, for other regions where regular flying service is to be established on a commercial basis.

Table 7. Average Annual Percentage Frequency of Upper Winds of Different Velocities at Selected Altitudes, Classified According to Wind Direction, for Middle Latitudes in the United States.

Wind Direction	Wind Velocity m.p.s. (m.p.h. in parentheses)											
	500 Meters (1,600 ft.)						1,000 Meters (3,300 ft.)					
	1–4 (1-10)	5–9 (11-21)	10–14 (22-32)	15–19 (33-43)	20–29 (44-65)	30+ (66+)	1–4 (1-10)	5–9 (11-21)	10–14 (22-32)	15–19 (33-43)	20–29 (44-65)	30+ (66+)
N......	1.9	2.2	0.9	0*	0	0	1.3	2.2	1.2	0.2	0.1	0
NNE...	1.8	1.7	0.3	0*	0	0	1.3	1.8	0.6	0.1	0	0
NE....	1.4	1.9	0.4	0*	0	0	1.8	2.3	0.5	0.1	0	0
ENE...	1.6	1.8	0.4	0*	0	0	1.6	1.4	0.2	0*	0	0
E......	1.2	1.5	0.6	0.2	0*	0	1.1	1.4	0.2	0.1	0*	0
ESE....	1.4	1.5	0.2	0.1	0	0	1.3	0.6	0.4	0.1	0*	0
SE.....	1.6	1.6	0.1	0.1	0	0	1.1	1.0	0.1	0*	0	0
SSE....	1.6	1.7	0.6	0.1	0	0	1.5	1.4	0.4	0*	0	0
S......	1.6	2.7	1.0	0.5	0.1	0	0.9	2.3	0.8	0.1	0*	0
SSW...	1.8	3.2	2.4	0.8	0.4	0	1.5	2.6	1.4	0.7	0.5	0*
SW....	2.0	3.9	3.2	1.4	0.3	0	1.8	3.7	3.6	1.6	0.6	0
WSW...	1.7	4.0	3.2	1.7	0.4	0	1.6	3.7	3.6	1.8	0.7	0
W......	2.0	5.3	3.9	1.3	0.1	0*	2.3	4.6	4.6	2.2	0.6	0*
WNW..	2.0	3.4	2.1	0.4	0*	0	1.5	3.2	3.8	1.4	0.3	0
NW....	1.6	3.2	1.3	0.2	0	0	1.5	3.9	1.9	0.6	0.4	0
NNW..	1.6	3.1	1.0	0.2	0	0	1.5	2.9	1.3	0.2	0	0
	Calm 0.4						Calm 0.2					
	2,000 Meters (6,600 ft.)						4,000 Meters (13,000 ft.)					
N......	1.3	2.3	1.1	0.5	0	0	0.5	1.3	0.4	0.7	0	0
NNE...	0.8	1.6	0.3	0.2	0	0	0.6	0.9	1.2	0.1	0.1	0
NE....	1.1	1.3	0.3	0	0	0	0.3	0.7	0.3	0	0	0
ENE...	0.4	0.5	0.1	0.1	0	0	0.9	0.4	0	0	0	0
E......	0.9	1.0	0.2	0	0	0	0.4	0.6	0	0	0	0
ESE....	0.6	0.5	0*	0	0	0	0.5	0.8	0	0	0	0
SE.....	0.4	0.7	0.2	0	0	0	0.7	0.1	0	0	0	0
SSE....	1.3	1.0	0.4	0.3	0	0	0.3	0.5	0	0	0	0
S......	0.9	1.2	0.6	0.1	0	0	1.0	1.5	0.6	0.3	0	0
SSW...	0.9	2.1	1.8	0.6	0.1	0	0.4	2.0	0.9	0	0	0
SW....	1.6	3.0	2.2	1.4	0.6	0	0.5	3.4	2.0	1.1	0.3	0
WSW...	1.1	4.0	4.8	2.3	1.0	0	0.8	1.6	1.8	2.0	1.0	0.4
W......	1.3	3.8	4.4	3.1	1.4	0.1	1.2	3.8	4.6	4.0	3.8	0.2
WNW..	1.4	5.0	4.6	3.8	1.8	0.2	1.0	4.2	6.0	4.5	2.9	1.1
NW....	1.6	3.4	3.4	2.4	0.9	0.1	1.8	5.2	6.2	4.4	2.8	0.4
NNW..	1.1	3.4	1.5	1.0	0.4	0	1.8	2.0	2.3	1.2	0.4	0
	Calm 0.1						Calm 0.3					

*Less than 0.05%.

Frequencies of different wind velocities at various levels, classified according to wind direction, and resultant wind values have been determined for all portions of the United States east of the Rocky Mountains and can be obtained in detail from the U. S. Weather Bureau.[11] In general, westerly winds have the largest percentage frequency of the higher velocities, and this distribution becomes more pronounced as higher levels are reached. Table 7 gives the values that have been determined for middle latitudes in the United States, i.e., Nebraska and Kansas eastward to Pennsylvania and Virginia.

The frequency of different velocities without regard to direction is shown in Table 8 for summer and winter and the year. The two groups are representative of the northern and extreme southern portions of the United States.

The figures in Table 8 and similar data, not here published, for other sections of the country may be briefly summarized as follows:

At the surface the frequency of winds of 10 meters per second (22 m.p.h.) or more is very small, averaging from 5% to 10%, with a maximum as a rule in spring and winter. There is no very marked variation in different parts of the country.

A decided increase occurs immediately above the surface as shown by the figures in the column for 250 meters (800 ft.). At "ordinary flying levels," i.e., 500 to 1,000 meters (1,600 to 3,300 ft.), winds of 10 meters per second (22 m.p.h.) or more occur from 20% to 25% of the time in the southern states and 40% to 45% in the northern, with a mean of 30% to 35% for the country as a whole. There is a fairly large seasonal range, from about 20% in summer to 45% in winter, the seasonal values as well as the annual being highest in the northern states. Velocities of 20 meters per second (45 m.p.h.) or more occur in general at these levels less than 5% of the time.

[11] Part II of "An Aerological Survey of the United States."

TABLE 8. AVERAGE SUMMER, WINTER, AND ANNUAL FREQUENCY OF UPPER WINDS OF DIFFERENT VELOCITIES IN THE LAKE REGION AND THE FLORIDA PENINSULA

LAKE REGION

Velocity m.p.s.	m.p.h.	Surface %	250 m. 800 ft. %	500 m. 1,600 ft. %	1,000 m. 3,300 ft. %	2,000 m. 6,600 ft. %	4,000 m. 13,000 ft. %	6,000 m. 20,000 ft. %
SUMMER								
0–9	0–21	99	87	79	74	63	56	55
10–19	22–43	1	13	20	26	35	38	38
20–29	44–65	0	*	1	*	2	6	6
30+	66+	0	0	0	0	0	*	1
WINTER								
0–9	0–21	94	73	61	49	27	15	13
10–19	22–43	6	27	35	46	61	45	36
20–29	44–65	0	0	4	4	11	33	34
30+	66+	0	0	0	1	1	7	17
ANNUAL								
0–9	0–21	95	77	67	59	43	36	36
10–19	22–43	5	23	31	38	49	44	40
20–29	44–65	0	*	2	3	7	17	18
30+	66+	0	0	*	*	1	3	6

FLORIDA PENINSULA

Velocity m.p.s.	m.p.h.	Surface %	250 m. 800 ft. %	500 m. 1,600 ft. %	1,000 m. 3,300 ft. %	2,000 m. 6,600 ft. %	4,000 m. 13,000 ft. %	6,000 m. 20,000 ft. %
SUMMER								
0–9	0–21	96	92	91	89	95	98	100
10–19	22–43	4	8	9	11	5	2	0
20–29	44–65	0	0	0	0	0	0	0
30+	66+	0	0	0	0	0	0	0
WINTER								
0–9	0–21	93	76	65	71	74	65	42
10–19	22–43	6	24	34	28	21	33	50
20–29	44–65	1	0	1	1	5	2	8
30+	66+	0	0	0	0	0	0	0
ANNUAL								
0–9	0–21	94	87	76	82	85	83	67
10–19	22–43	6	13	24	18	14	16	31
20–29	44–65	*	0	*	*	1	1	2
30+	66+	0	0	0	0	0	0	0

*Less than 0.5%.

At greater heights the seasonal and latitudinal variations increase very decidedly, as well as the frequency of the higher velocities themselves. For example, at 4 and 6 kilometers (13,000 to 20,000 ft.) winds of 10 meters per second (22 m.p.h.) and more occur in the northern states 45% of the time in summer, 85% in winter, and 65% for the year; in the southern states except Florida the values are 30%, 75%, and 50%, respectively. Winds of 20 meters per second (45 m.p.h.) or more are observed in the northern states 5% of the time in summer, 35% to 40% in winter, and 20% for the year; in the southern states, again excluding Florida, 0%, 30%, and 15%, respectively. In the Florida peninsula high winds occur so rarely, even at great heights, that they can be ignored so far as their effect on flight is concerned.

Resultant winds. Reference has been made to the importance of the resultant winds in the determination of flight schedules, and it was shown that the resultant wind at about 500 meters (1,600 ft.) between New York and Chicago agrees closely with the average difference in time maintained by planes in eastward and westward flights. Figure 36 gives the summer, winter and annual resultant winds at 500 and 1,000 meters (1,600 and 3,300 ft.) above the surface in the eastern and central portions of the United States. The features of chief interest brought out in this figure and in the values for higher levels, not here included, may be summarized as follows: (1) The resultant direction has a west component at all levels in the northern states. In the extreme south an east component is found from the surface to nearly a kilometer (1,600 ft.) above it during most of the year and at all heights during summer. (2) The resultant velocity at and near the surface is small because there is a fairly equal distribution of all directions, but the velocity noticeably increases with height as the individual directions become more and more grouped in the west quadrant. (3) There is a pronounced variation in these

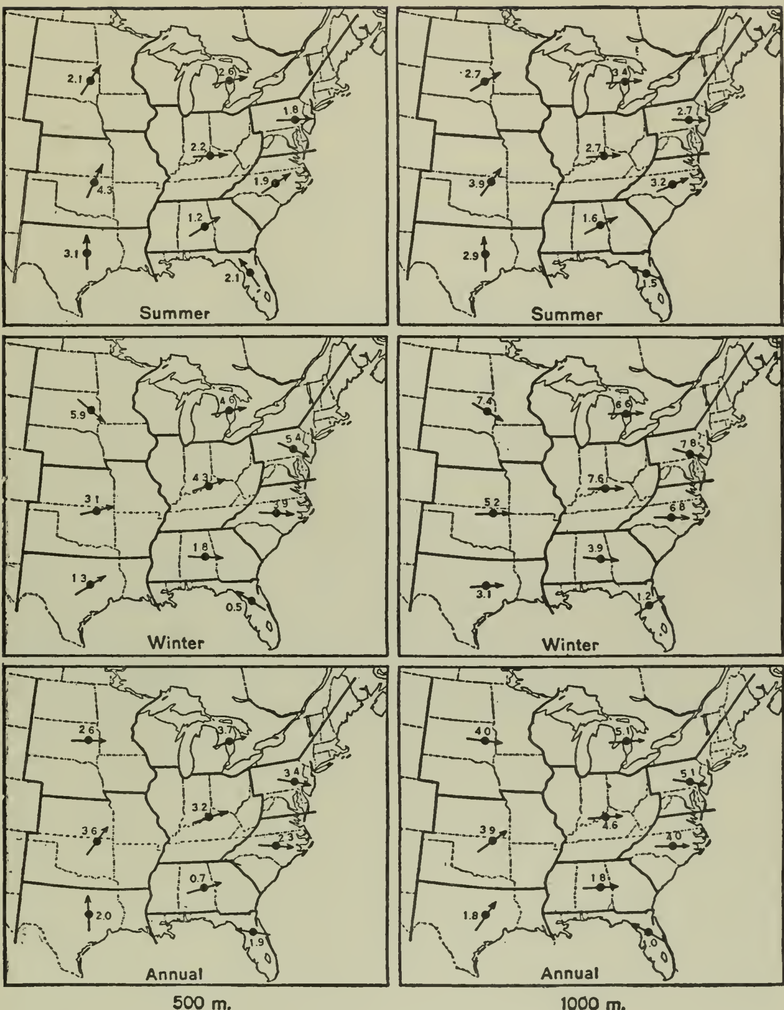

Figure 36. Summer, Winter, and Annual Resultant Winds at 500 and 1,000 meters (1,600 and 3,300 ft.) Above Surface in Eastern and Central United States

To convert m.p.s. to m.p.h., multiply by 2.2.

velocities with season and latitude, especially in the higher levels.

Winds at very high altitudes. The highest velocity ever observed at any height is 83 meters per second (186 m.p.h.) at 7,200 meters (24,000 ft.) above Lansing, Mich. It is probable that even higher velocities than this occur at times, but they are certainly very infrequent, and, when they do occur, they are probably extremely short-lived. Unfortunately, reports in the press, based upon one or two experiences in airplane flights, have given to the public the impression that winds of nearly constant westerly direction and of high velocity, "200 or 300 miles per hour (90 to 135 m.p.s.)" are the rule in the upper flying levels, 5 to 10 kilometers (16,000 to 33,000 ft.). Actual observations extending over a period of 12 years, some 250,000 in all, show conclusively that winds of these velocities very rarely, if ever, occur. As for the direction, although in general it has a west component, yet it varies widely from day to day, usually between north-northwest and south-southwest, but occasionally coming from an easterly point. By no legitimate stretch of the imagination can the wind at any height over the United States be described as "a trade wind of 200 to 300 miles per hour from the west."

CHAPTER 5

FOG

By Vincent E. Jakl

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Fort Crook (Omaha), Neb.

Formation. Fog may be considered as cloud lying on the surface of the earth. It differs from cloud only in the circumstance that it forms in surface layers of air instead of aloft. Cloud forms whenever the amount of moisture in the air becomes greater than can exist without condensing at the prevailing temperature. At any temperature, air can contain only a definite amount of moisture in invisible form. When the air has that amount of moisture mixed with it the air is said to be saturated.[1] This limiting amount depends on the temperature; the higher the temperature, the greater the possible amount of water vapor.

When unsaturated or dry air is cooled, the saturation point is eventually reached and condensation of the invisible water vapor into visible dew, fog, or cloud particles begins. The air is said then to have reached its dew-point. Therefore, for every state of air there is a certain temperature known as its dew-point, to which it must be cooled before condensation begins. The proportion of moisture in the air to the amount necessary for saturation at the prevailing temperature is called the relative humidity. Thus if air contains only half of the amount of moisture necessary for saturation, the relative humidity is 50%; when saturated, the relative humidity is 100%.

The cooling of air to its dew-point is the chief cause of the

[1] See footnote 1, Chapter 3

formation of fog and cloud. While clouds are usually formed by air rising above the surface and cooling, the rising of air is one of the very causes that dispel fog or hinder it from forming. We must therefore look to other processes to explain the attainment of saturation near the surface, essential to fog formation. Usually, such saturation is accomplished by cooling of the air to its dew-point, but other processes contribute to it, all of which may be classified as follows:

1. *Radiation.* The cooling of the ground and the air layers immediately above it.
2. *Advection.* (a) The passing of warm, moist air over relatively cold surfaces. (b) The passing of cold air over a warm, moist surface.
3. *Mixture.* The mixing of moist air masses of different temperatures.
4. *Expansion.* A decrease in the pressure of the air without leaving the surface.

An almost invariable accompaniment of fogs, at least of dense fogs, is an "inversion" in temperature. By this is meant an increase in temperature with height above the surface instead of the normal decrease. An inversion in temperature in the lowermost layers of air is common on clear nights when the wind is light or comparative calm prevails. It also occurs whenever warm air overruns a cold layer near the ground, or a cold wedge of air underruns a warm mass of air. This inversion acts as a barrier above which the fog cannot extend, and is indeed often the very result of the same radiational cooling that causes the fog.

Any marked fall in temperature with height to or beyond the adiabatic rate, combined with turbulence causes the air near the surface to rise which process results in the formation of clouds. The compensating descending current must become warmer and drier as it approaches the surface, and therefore prevent the formation of fog, or dispel fog if already existing. Fogs, particularly light fogs, may occur when there is no

change or a relatively small fall in temperature with height, the necessary condition being a fall in temperature with height insufficient to cause pronounced vertical exchange of air. Vertical movement of air is also caused by vigorous winds, particularly when passing over rough ground. Well-defined horizontal pressure gradients in the air with their attendant winds of marked force are therefore another preventive of fog.

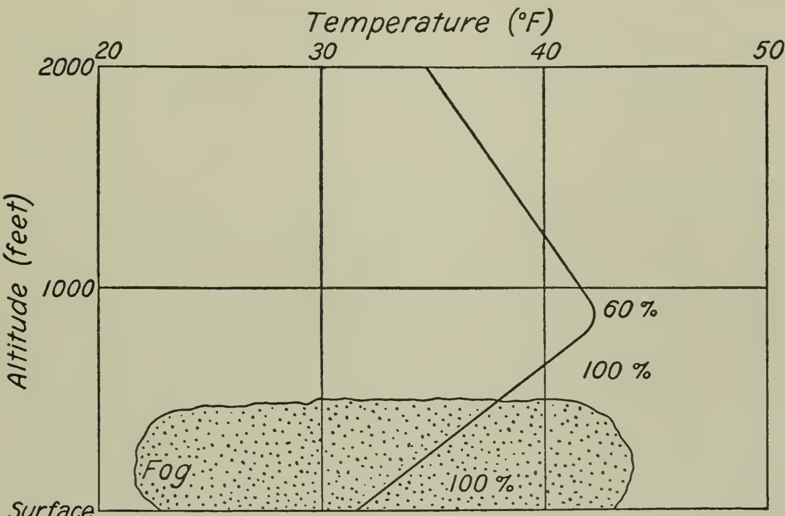

Figure 37. Temperature-Humidity-Altitude Curve for Typical Fog-Forming Conditions

To convert feet to meters, multiply by 0.3; ° F. to ° C., subtract 32 and multiply by 5/9.

Two of the prime requisites for dense fog are therefore an inversion in temperature extending from the surface upward and comparative calm. Figure 37 is an ideal temperature-altitude-humidity curve, showing the change with height of these elements in the order commonly associated with fog formation. Ordinates are heights above the surface, abscissae are temperatures, and relative humidities are plotted directly on the curve. It will be noted that the fog occurs at the base of the inversion, i.e., where the temperature begins to rise with height. Warmer air being above, the fog cannot rise.

Over continental regions removed from seas and large inland bodies of water, fogs, in general, occur much more frequently in the colder than in the warmer season. Over northern seas[2] and on certain sides of large inland bodies of water, they occur much more frequently in summer than in winter. Over the continents, at least in the temperate zone, the variation in fog frequency with latitude is small; over the seas it is large, the northern seas having an abundance of fog, while as tropical waters are approached the number of fogs becomes vanishingly small. Moreover, the seasonal variation over southern seas is opposite to that of the northern seas, such few fogs as are observed over southern waters being confined entirely to the colder season.

A number of causes contribute to the winter preponderance of fogs over inland areas. In winter the average fall in temperature with height is less than that during summer, and inversions in temperature in the lower levels are frequent both day and night. This results in restricting the vertical ascent of air, and thereby promotes the building up and accumulation of high relative humidities near the ground. Furthermore, smaller quantities of moisture are required to bring air to saturation at low temperature than at high, a fact that is of importance when considering the amount of moisture available for condensation in mixture processes.

The varying length of day and night with the seasons has an important bearing on the formation of all fogs in which nocturnal radiation plays a part. The long hours of sunshine on a summer day heat the surface layers of air with a resulting low relative humidity, while radiation during the comparatively short night is insufficient to bring the temperature down to the dew-point. In winter, the short days curtail heating and convectional ascent of surface layers, while the long nights promote radiational cooling.

[2] References in this chapter to latitude all apply to the northern hemisphere.

Dense fogs indeed occur over continental regions in the height of the warm season, and at temperatures that are not necessarily below the seasonal normal; in fact, they may be above normal. The proper conditions for fog, while infrequent in summer over inland regions, nevertheless occasionally occur. A cloudy, showery day for example, followed by a clear, still night, can easily result in fog, even in midsummer.

Fogs on coasts partake to a large extent of the characteristics of the sea fogs appropriate to the latitude; elsewhere they may have more of the land characteristics, or show both influences, depending on the exposure and the nature of the prevailing winds.

Radiation. Nocturnal radiation in clear weather causes the temperature of the ground to fall rapidly. However, if the overlying air is moist, this cooling is soon checked by the deposit of dew (or frost) as soon as the air layer immediately above the ground is cooled to its dew-point. The deposit of dew, in fact, diminishes the total amount of moisture in the air. The conduction of heat through the air is a very slow process; theoretically, the coldness of the ground cannot be communicated in appreciable degree to the air above it in the course of a night. The molecular diffusion of moisture through the air is likewise a process as slow as the conduction of heat. Moreover, the direct radiation of heat from the air to space cannot cause a cooling of more than a few degrees throughout a night. These facts would seem to argue against radiation as an effective cause of fog of more than a few feet in depth.

The explanation is partially given in the statement that a slight turbulence comes into play, causing a mixture of air extending from the ground to a short distance above, which may be a few feet or a few hundred feet. The air is seldom absolutely calm, as anemograph records of any station will amply prove. The slight turbulence resulting from these light winds is sufficient to cause the necessary mixing, and yet lacks

the depth necessary for any appreciable convectional activity. Any vigorous convectional movement would cause adiabatic changes in temperature that would prevent fog formation. Therefore, the radiational cooling of the ground is consumed, so to speak, in cooling the overlying layers of air rather than in causing a very low ground temperature. The mixing process referred to will be treated in a later paragraph.

Radiation fog very often builds up by gravitation. As soon as the lowermost layers cool by radiation, they become denser and will flow down the slightest incline and be replaced by other air which in turn cools also and flows downward. If the surface were perfectly level, and absolute calm prevailed, only dew could result, or at best only a fog knee deep. This is in substance the explanation of the universally observed fact that valleys and other low places are more susceptible to fog than those that either rise above their surroundings or form part of extended level plains. Plate XXIV illustrates a typical valley fog.

Another aspect to this accumulation process is that rivers and small lakes may be fogged over when the adjoining land is clear, due to the fact that the air along the shores and valley sides has cooled nearly, but not quite down to the dew-point. On accumulating over the relatively warm water surface, supersaturation and fog result. On the other hand, a river flowing through a comparatively flat valley may be free of radiation fog or only covered by a "steam mist," while the adjoining land is befogged. The explanation is that radiational cooling of the water is too slight to cause fog directly over the river, and there has been no accumulation of fog or cooled air toward the river from the land.

The nature of the terrain has a considerable influence on the incidence of fog. Differences in this respect are determined by the varying absorbing and radiating qualities of different surfaces. Thus, a field with a good stand of growing crops, a woodland or a snow-covered surface may be more

Mount Wilson, Calif. F. Ellerman

Plate XXIV. Valley Fog and Cirro-Stratus Clouds

easily fogged over than a plowed or stubble field or a short grassed pasture. Landscaped residential blocks in a city may be fogged over when the intersecting paved streets and the business districts are comparatively free of fog.

In this connection reference is made to a comparison of dense fog frequency at adjoining country and city stations for the same period of record, the stations being respectively Drexel and Omaha, Nebraska, 20 miles (32 km.) apart. The average annual frequencies are 13 and 7, respectively. The small annual average of 7 at Chicago is also cited. The smoke of cities undoubtedly prolongs fog once it has occurred, and probably increases the frequency of light fogs. Considering pure dense fogs, however, it seems likely that under equal climatic conditions they are more frequent over country districts than over large cities. This is of more or less academic interest, as the smoke nuisance in the vicinity of large cities more than offsets any slight immunity from fog that they may possess as compared with outlying country places. A practical side of the question, however, is that occasionally in widespread fogs, the heat of a city may cause enough thinning of the fog to aid the pilot in finding the city and its airport.

Radiation fog usually builds up rather late in the night, the average greatest frequency being during the hours just before and after sunrise, with the peak hour immediately after sunrise. This peak hour of average frequency does not of itself mean that the first hour of sunshine has any intensifying influence on fog formation. The usual time for the minimum temperature of the day to occur is about or just before sunrise. Fogs, therefore, are very likely to form shortly before sunrise, and having once formed it takes the sun a few hours to dissolve them.

From the foregoing facts it is apparent that the average time of ending of radiation fogs is further removed from the time of sunrise than the average time of beginning, and

the curve of average frequency will therefore show a peak after sunrise. In this country at least, the great majority of inland fogs begin in the night, usually, as already stated, shortly before sunrise. Observations show, however, both in this country and in Europe, that fogs often begin soon after sunrise. One suggested explanation is that sunshine has a marked effect in increasing the hygroscopic effect of gases and suspended particles in the air. It has been known for some time that fog and cloud require nuclei in the form of hygroscopic particles for atmospheric moisture to condense on, in other words, that condensation will not occur in pure clean air, even when cooled considerably below the dew-point. Such particles are always present in the air in variable quantities. They consist largely of the products of combustion; suspended salt particles in sea air also contribute to this class of nuclei.

An examination of the records of any station will show conclusively that fogs apparently due to radiation are not always contingent upon the cooling of the air to the dew-point; the dew-point is often reached, there is some further cooling, but fog does not evidence itself until a rise in temperature and more or less mixing of the air take place. We therefore have to deal with air movements that will be discussed later under advection fogs. Another possible cause of fogs beginning after sunrise is apparent in the foregoing, i.e., the temperature of the ground and lowermost layers of air is still low, even though the sun is already above the horizon, and the increased general air movement engendered by the sun furnishes the final stage in the fog forming process.

Condensation can take place on hygroscopic nuclei before full saturation of the air has been reached, and light fog is formed. Dense fogs require full saturation. Light fogs occur with smoky, hazy states of the air, with rains and snows, and steaming from the ground.

It is supposed that sometimes fog builds up by continued radiation from the top of the fog after it once forms over the ground. It is not likely, however, that such a process can result in fog to any appreciable depth. A somewhat related process that can build up fog soon after sunset is the circumstance of hazy, humid air with light wind and clear sky. Radiation then proceeds directly from the air and fog is built up quickly. It is appropriate here to state that the capabilities of air for radiating directly to space and to the colder ground vary with the amount of moisture and impurities in the air, increasing as these components become greater. On the other hand, moisture and impurities hinder the passage of heat rays through the air. It is evident, then, that the type of fog just mentioned is best realized with a shallow stratum of moist, hazy air with clear, dry air above; therefore such a fog, while it forms quickly, must of necessity be quite shallow, yet often deep enough to obscure all the usual landmarks of an airport. The dissolving of radiation fog usually takes a few hours of sunshine; it is accomplished partly by the direct heating and evaporation of the fog by the sun, and partly by being broken up and carried away and upward by the air movements that begin soon after sunrise. Plate XXV is a good illustration of lifting fog.

A favorite situation for radiation fog is in the crest and edges of high-pressure areas. Fog is not likely to form in fresh, cold, high-pressure areas, certainly not in their front, because of the fairly vigorous air movement and also because the temperature decrease with height in the lower layers causes too much turbulence. The Highs must have aged and degenerated so to speak, i.e., subsidence must have caused inversions in them before they can be appraised as generators of fog. Other favorite places are in the periphery of weak, low-pressure areas, particularly the northeast, east, and southeast sectors, and in general in places of weak pressure gradients with pressure not far from normal.

Mount Weather, Va.

Plate XXV. Lifting Fog

Advection (a). Fog at sea usually occurs by advection. Air that has passed over warmer waters becomes heavily laden with moisture, and then passing over colder waters, cools in the lower layers. Aided by a slight turbulence and mixture with the moist air already overlying the cool water, a dense fog results. Conspicuous examples are found in the region of the Newfoundland Banks, where warm air from the Gulf Stream passes over the colder waters of the Labrador current. Another example is the fogs of the California coast, where air from the Pacific passes landward over the relatively colder coastal waters. It is also formed in the warmer season of the year when air drifts from the warm land over comparatively cool bodies of water; in this case, however, it must first acquire a maritime character before it can form fog, as it leaves the land quite dry. It is not likely to form on rivers or small lakes by advection, except at the mouths of rivers in winter, if the air circulation is such as to bring the air from the larger body of water over the relatively colder river waters.

Advection fog forms when sea air blows onto colder land, but this simple condition by itself does not necessarily assure fog. The contrast in temperature must be pronounced, and the time preferably night. Such fogs do not easily form in daytime. The summer fogs on the California coast are not directly due to contrast in land and water temperature, because there the air movement is actually from the colder water to the warmer land. They are sea fogs that have been carried onshore by the sea breeze, which in turn is caused by the contrasting land and water temperature. Farther inland they become a low cloud.

Fog by advection occurs most frequently over seas and large inland bodies of water in the summer, and over the land in winter. It requires horizontal contrasts in temperature, which over the land are pronounced in winter and only slight in summer. Over the sea, the contrast in water temperature is large

in summer, because the northern waters are kept cool by floating ice. Moreover, much of the air that passes over the northern waters has had its origin over the heated continent.

Large inland bodies of water are likewise colder than the surrounding land in summer; and are therefore commonly subject to fog at that time of year. In winter large inland bodies of water do not cause advection fog except very locally, even though they are then considerably warmer than the surrounding land, because the wind that blows over the lakes has generally had its origin over the cold land areas, and the result is cloud instead of fog.

Advection fogs, unlike radiation fogs, are not limited almost exclusively to the night and early morning hours; they may form at any time of day, but over the land they are not likely to be dense in the afternoon hours. Over the sea and immediate coast line, they can be dense at any hour. This is well evidenced in Plate XXVI, the photograph from which it is reproduced being obviously taken by day. This illustration also strikingly shows another feature characteristic of many sea fogs, i.e., that they often occur in separate masses or ridges with clear air between and with wall-like edges.

Advection fogs over the land, parallel to the simple process producing them over the sea, are difficult of realization. In the general problem of interchange of temperature between surface and air, the principle is established that over the sea, moving air takes on the temperature of the sea, the sea itself being but slightly affected by the air temperature. Therefore, air in the lower strata, being already close to saturation, soon becomes foggy as it passes over colder seas and acquires the temperature of the colder waters. Over the land, quite the reverse is true. The relatively thin upper crust of poor conducting earth is easily affected by the temperature of the air, so that, disregarding other causes, air plays the dominant rôle, and the ground much more quickly and completely ac-

quires the temperature of the air blowing over it than does a water surface.

With a given condition of horizontal temperature gradient over land, it does not necessarily follow that air blowing over continuously colder land will become fogged, unless it is already nearly saturated. Such high humidity of the air usually has its inception in causes other than advection. Excepting then the condition of air initially of high moisture content, its progress toward colder regions will have the following results. Under certain weather types, this air will override the colder air immediately in front of it and cause cloud instead of fog. Under other circumstances again, this air will displace the colder air in front of it, become slightly cooled, and in turn warm the ground. The air succeeding it will also become slightly cooled, but will be passing over ground already slightly warmed. The consequence will be the often observed phenomena of temperature at a place rising during the night, even in clear weather with snow-covered ground, but with no fog, or at the most only a very light fog. Air that is to become fogged must be kept hemmed to the ground; to meet the requirements it must be both warmer than the region to which it is passing and colder than the air immediately above it. Such a circumstance is realized when two distinct air masses take part, for example, a relatively cool, moist current from the east, southeast, or south, surmounted by a warm, dry current from the south, southwest, or west. The lower air is coming from a slightly warmer region, but has already been cooled to a fair degree of saturation by radiation, or has its origin in a cloudy or rainy region.

Under the last-named circumstance, moderate to dense fogs may form over the land in the daylight hours, the usual weather situation being that the foggy area is in the general front of a weak low-pressure area where the pressure gradients happen to be weakly defined. Where advection seems to be associated with radiation, cases may be cited where the tem-

Plate XXVI. Fog Bank—View Taken from Ship

perature is lower in the front of a Low than in the rear, with cloudy, slightly showery weather prevailing in the cooler area, and warmer air aloft. Such a Low is likely to be weak or dying, and if the weather clears up at an opportune night hour, advection and radiation combine their effects, and fog will quite certainly form in the previously cloudy, showery area.

The weather types mentioned in the last paragraph may often, in the terminology of "fronts," be classified as warm fronts and occlusions. Fogs under such situations may begin in the character of dense fogs any time from late afternoon until early morning; their duration may vary from a few hours to a period comprising all the night and twilight hours, depending on the activity of the weather type concerned. They may begin in the late daylight hours and end in the night.

When the coldest air in the lower layers is not immediately above the surface but rather a few hundred feet high, with an inversion in temperature still higher up, the prevailing condition is then likely to favor the formation of low clouds, mists, and light fogs. The fogs may become moderate to dense at nightfall, but probably not equaling the density of true radiation fogs. Such a condition may be widespread and persistent for a number of days, and is most likely to occur in the general front of certain types of low-pressure areas, and in the rear of some high-pressure areas.

Figures 38 and 39 are presented to show the relative frequency of fogs in different segments of Lows and Highs. The figures are based on a long series of observations at Davenport, Iowa, a typical inland station in the United States.[3] The circles represent the outside circumference of an average low-pressure area of 1,000 miles (1,600 km.) radius, and the outlined areas within the circles represent frequencies of fog given in percentages of times that Davenport fell in the respec-

[3] Anton Udden, "A Statistical Study of Surface and Upper Air Conditions in Cyclones and Anticyclones Passing Over Davenport, Iowa," *Monthly Weather Review*, Vol. 51, pp. 55-68, February, 1923.

tive portions of low- and high-pressure areas. The study from which the figures are reproduced includes all fogs, irrespective of their intensity or their cause.

A process similar to that which takes place in advection fog of the (a) type is involved when cold rain falls through warm air. In thunderstorms and in other heavy rains or

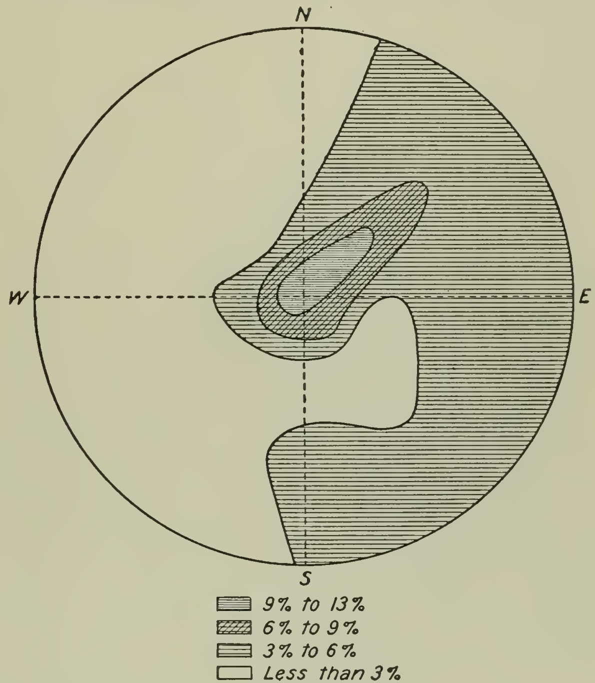

Figure 38. Percentage Frequency of Fog in Various Portions of Lows at Davenport, Iowa (after Udden)

in heavy snows, chilling of the air down to its dew-point may result. Once the dew-point is reached and passed, a heavy fog must of consequence follow, to which the precipitation itself lends obscurity to a state of zero visibility. The forecasting of such fogs therefore amounts to forecasting the intense precipitation that causes them, and is quite independent of the peculiar conditions favoring the formation of fog without precipitation. If the rain does not chill the air to its dew-

point, dense fog cannot result, but a light fog can be formed due to mixture of air about the raindrops.

Advection (b). It is sometimes stated that cold air blowing over warm, moist surfaces is an important cause of fog. This is not borne out either by observation or a consideration of the dynamic processes involved. The lower layers of air

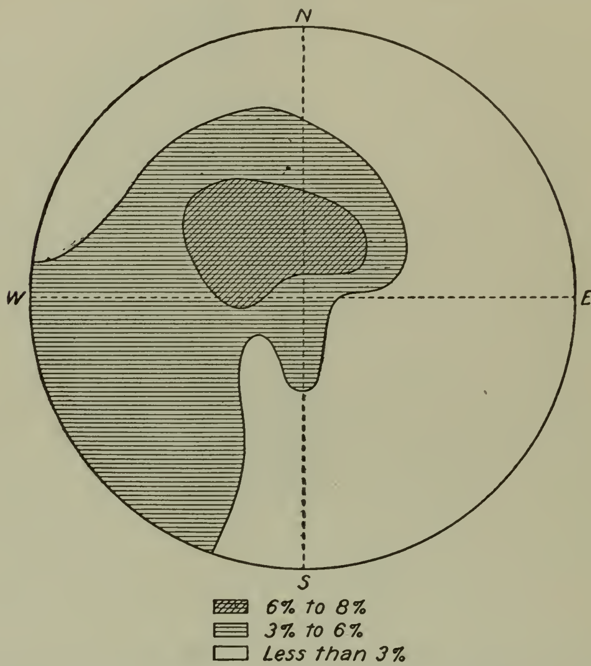

Figure 39. Percentage Frequency of Fog in Various Portions of Highs at Davenport, Iowa (after Udden)

are warmed and must soon rise, resulting in clouds or precipitation, but seldom fog, unless one chooses to call fog the "steam" that rises over a warm, moist surface. The "steam" or "sea smoke" in such cases is due to the rapid evaporation from the warm surface, causing supersaturation along with a rise in temperature of the cold air, in the same manner as hot water under ordinary circumstances.

The most pronounced examples of this phenomenon are found over stretches of open water in Arctic regions that are exposed to intensely cold air that has been chilled by radiation over extensive ice-covered areas. Where the cold air mass is quite shallow, that is, surmounted by warmer air a short distance above the surface, so that vertical convection cannot proceed to any great height, dense fog may result. Fog by this process can form more easily over Arctic regions than elsewhere, because at very low temperatures it requires a small amount of moisture to befog the air. A small amount of heat is therefore taken up from the warm water surface, and consequently only a feeble tendency to vertical convection results.

It is possible that this type of fog may occasionally occur over northern waters not necessarily in Arctic regions, and perhaps even over continental areas, if the requirements for extreme temperature stratification are satisfied. Reports of fog at sea where the observations of water and air temperature and wind direction seem to confirm this process of fog formation are not lacking. Probably the only examples over continental regions are those cited under radiation fogs, as where a cooled, moist air mass of very limited depth drifts over a warm river or lake surface. This usually gives rise to the early morning "steam mists," characteristic of rivers and inland lakes on clear autumn mornings, and under exceptional conditions may result in dense fog.

Advection fog under process (b) suggests another type of "rain" fog, that is, fog formed by warm rain falling through cold air, as distinguished from fog formed by cold rain falling through warm air. This condition is more favorable for fog formation than that of cold air passing over a warm, moist surface, because in the former case the cold stratum of air above the ground is warmed rather uniformly by the rain, while in the latter it is warmed at the base and sets up vertical convection. Nevertheless, even this form of

supersaturation of air usually gives rise to only light to moderate fogs. The weather situation is similar to that typical of sleet and freezing rains, characterized by a more or less widespread area of low clouds, the dominant feature of which is warm, moist air overrunning a cold lower stratum and causing rain at a higher temperature than that prevailing near the ground.

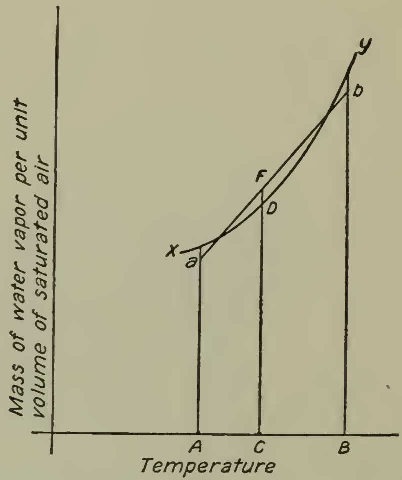

Figure 40. Temperature—Saturation Curve (after von Bezold)

Mixture. It is probable that few fogs are entirely dis-associated from a mixing process. It was formerly thought that precipitation was formed by that process. It is now definitely known that mixture of air masses of different temperature, even if saturated, cannot produce appreciable precipitation, but that it does form cloud and fog. The graph shown in Figure 40 plainly illustrates this. Abscissae are temperatures, and ordinates absolute moisture in terms of either grains of water per unit volume of air or vapor pressure. The curve is drawn through points representing the amount of moisture contained in saturated air at different temperatures.

Taking as an example the mixture of two air masses of nearly saturated air of temperature *A* and *B,* the average tem-

perature of the mixture will be represented by the point C between them, and the moisture content of the mixture by the line CF. At the temperature C, however, the capacity of the air for moisture is represented by the line CD. Therefore DF qualitatively [4] represents the amount of moisture in excess of that needed for saturation, and which will be condensed as visible vapor.

Fog formation under conditions where mixture would seem to play the dominant rôle, obviously belongs to weather situations where air masses of different temperature flow side by side. It is hardly conceivable that such a dividing surface can occur in nature in a perpendicular direction, except perhaps very locally. Such surfaces can occur on an incline and are associated with so-called "fronts," i.e., cold fronts, warm fronts, etc., representing cold air underrunning warm air, and warm air overrunning cold air, respectively. On the boundaries clouds form, and where the sloping boundary surfaces intersect the ground, fog may sometimes occur. Apparently such fogs can form only to the extent of comparatively narrow ribbons. In a more or less local way, isolated air masses may cause a mixture fog, as for example the fogs that sometimes occur after thunderstorms. It is probable that most instances of mixture process forming fog, occur when the mixing takes place in a vertical direction, where the height involved is sufficient to embrace air of different densities, but insufficient to bring about pronounced adiabatic changes in temperature.

Expansion. Air may undergo fall in pressure without leaving the earth's surface by flowing from a place of high pressure to one of low; by a general simultaneous fall in pressure due to dynamic processes, or by passing up an orographic slope. The result is similar to that which takes place when

[4] The short line DF cannot strictly be taken as a measure of the amount of moisture available for condensation, because the latent heat of condensation will cause the temperature of the mixture to be higher than that shown by C, and therefore less condensation will take place than shown by DF. However, so long as the line ab intersects the curve xy, some condensation is bound to occur.

air rises vertically—it expands adiabatically and cools. Excepting the ascent of air up an orographic slope, cases where fog can be attributed solely to adiabatic cooling are probably rare, mainly because on the one hand the conditions causing pronounced falls in pressure are usually associated with considerable air movement and turbulence, and on the other, because the temperature fall from this cause can be only slight compared with other factors influencing air temperature. At ordinary heights above sea level, a fall in pressure of one-tenth of an inch (2.5 mm.) would cause a drop in temperature of only about one-half degree F. (0.3° C.). A tenth of an inch gradient in 100 miles (1.5 mm. in 100 km.) or a tenth of an inch (2.5 mm.) fall in one hour represents a fairly pronounced situation. A change in temperature of one-half degree in 100 miles (160 km.) or in one hour is small compared with other causes of air temperature changes.

The circumstance of air rising up an orographic slope is perhaps the most common cause of fogs under this head. Undoubtedly, under certain conditions, all three methods producing pressure fall aid in the formation of fog that is already developing from other causes.

Mountain fogs. It will readily be seen that mountains or ridges jutting upward will be fogged-in whenever general cloudiness prevails, because the lower type of clouds are in a sense only elevated fogs, notwithstanding that they are formed by processes different from those of fog. The higher portions of isolated mountains or ridges have insufficient area to affect the general trend of weather conditions, and obviously must be fogged-in during a considerable portion of the year, depending on the average cloudiness of the region in which they lie. Frequently the clouds are high enough so that the passes are clear.

Extensive mountain ranges, of course, affect the general weather situation, one feature of which is that they deflect the winds upward, causing forced ascent of air on the wind-

ward sides, and consequently precipitation, especially if the prevailing winds are from a moist region. This contributes to the general cloudiness, which over a mountain region means fog, especially over the more jagged portions. On the lee side of the range, there is more or less descent of the air and therefore adiabatic heating, which together with the fact that the rains have deprived the air of considerable of its moisture, makes the air quite dry and therefore quite unlikely to become foggy.

The mountain characteristic applies sometimes to slight eminences of a few hundred feet, if the cloud blanket is low enough. While cloud layers to some extent parallel the general trend of the plain over which they are suspended, they do not conform in contour to all the irregularities in elevation of the ground. Therefore, in cases of low clouds, one place may have a ceiling of a few hundred feet and fair visibility, while another a short distance away and only a little higher will report dense fog.

Disregarding the purely mountain influence, it is of interest to consider the bearing that altitude alone has on the relative frequency of fog. For a number of reasons, the humidity over an elevated plateau is usually low. Moreover, considering Figure 40 and the footnote qualifying it, it will be noted that mixture, almost inevitable to all fog formation, will not produce as much condensation in rarefied air as in dense air, owing to the fact that the latent heat of condensation will be more effective in raising the temperature in the former than in the latter case, and consequently there will be less moisture in liquid form available to make fog. This seems to be confirmed by the statistics for different stations, after making due allowances for other modifying influences.

Drift fog. The drifting of fog from place to place is an important factor in the occurrence of fog at sea. Over land areas, however, the occurrence of fog can very seldom be attributed to the mere drifting in of air already befogged.

Even in coast regions, fog that drifts in from the sea envelopes only the immediate shore line; farther inland it either dissipates or becomes a low cloud. In general it may be said that fog does not occur over any land area unless the conditions there are already ripe for its formation. The occasional exceptions to this rule occur under conditions of abrupt shift in wind, when fog may be transported a short distance. In all cases of transport of fog over land areas its duration is short.

Height of fog. Sea fogs occasionally extend to 3,000 or 4,000 feet (900 to 1,200 m.) in height, or perhaps even higher. From the meager statistics on the subject, a height of 400 to 500 feet (120 to 150 m.) may be laid down as an approximate average. Often they are so shallow that the deck of a vessel may be enveloped in fog, while the mastheads are in the clear air. The same estimate of height applies on coasts to fogs that have drifted in from the sea.

Fogs on land range from a few feet for the shallowest of radiation fogs, to probably 1,000 feet (300 m.) or so for advection and heavy radiation fogs. The accumulation of radiation fog in valleys undoubtedly at times extends to a few thousand feet in height. For ordinary level country, 100 to 200 feet (30 to 60 m.) may be given as a fair estimate of their average height.

A condition of dense cloudiness with the base of the clouds close to the ground, may often be associated with fog of varying degrees of intensity lying on the ground. If the clouds extend to a considerable height, the situation may be summed up as a "fog of great height." However, it is unlikely that dense fog on land ever blends into clouds to form an unbroken stratum of dense fog extending to great heights; because as hereinbefore stated, dense fogs, irrespective of how they are formed, require comparatively clear, warm air aloft at a not very great height.

Duration of fog. Over most inland regions light fog occurs on an average of three times more often than dense

fog. Light fog is often recorded as the initial and final stages of dense fog, but more frequently it occurs independent of dense fog. The average duration of light fogs is 5 to 6 hours, and of dense fogs probably about 4 hours. The duration in individual cases is, of course, extremely variable. Radiation fogs show the most constant period of duration, beginning as they do usually in the early morning hours and ending in the middle of the forenoon. In exceptional cases, however, the conditions favoring fog may be persistent day and night over a period of days, with a temporary letting up only in the middle of the afternoon.

There is also a seasonal variation in the duration of fog. Over land areas, fogs are more prolonged in winter than in summer, probably in about the ratio of 2 to 1. A fair approximation for radiation fog may be about 5 to 6 hours for winter fogs to 2 or 3 hours for summer fogs. Over northern seas and inland regions affected by sea fogs and lake fogs, the seasonal variation is reversed, the fogs lasting longer in summer than in winter. Moreover, all fogs of a maritime nature have an average duration considerably greater than those of a strictly land character, and under peculiar conditions like those of the lower Pacific coast, are more likely to occur in the day than in the night.

Artificial dispersion of fog. No method thus far developed for artificial dispersion of fog—even though successful in laboratory or small-scale experiments—is applicable to the problem on a large enough scale to give the desired results. The methods that usually are advocated involve the spraying of electrified sand, heating the fog, and draining the befogged air into underground chambers. The difficulty lies not only in the large volume of foggy air that must be dealt with, but in the fact that the fog is seldom still, and new masses of fog therefore would have to be continually dispersed or removed at the expense of more energy than can be practically or economically applied by present methods.

Distribution of fog in the United States. Table 9 gives monthly and annual dense fog frequencies for coast and interior regions. Considering first the coast regions, it will be noted that there are more fogs on the Pacific than on the Atlantic, the difference being more particularly evident in the middle and lower latitudes. This is due in part to the prevailing west winds, which blow onshore on the Pacific and offshore on the Atlantic. Over the north Atlantic, however, winds are brought onshore by low-pressure areas, the paths of which have a tendency to converge toward the New England states before passing off to sea.

The summer characteristic is the predominant one along the immediate north Atlantic and north Pacific coasts, and is very marked along the middle and lower Pacific coasts. Ocean fogs are most frequent at this time of year over northern seas; while the special condition of cold coastal waters on the lower Pacific coast is effective in extending this summer characteristic much farther south along the coast line of the Pacific than along the Atlantic.

On both the Atlantic and Pacific, the summer type is due to fogs that have formed at sea and are carried onshore by the winds. Places that have a good sea exposure show this type of fog most strikingly, as for example Point Reyes on the Pacific, and Nantucket on the Atlantic.

The averages for the winter months are contributed partly by fogs that are continental in nature, that is, fogs that occur independently of the sea, and partly by fogs that are caused by the relatively warm, moist oceanic winds blowing over the cold land. This undoubtedly explains the averages for some places that show no pronounced seasonal variation, as for example, San Francisco on the Pacific, and Atlantic City on the Atlantic.

Where fog drifts onshore from the sea, it is due either to the general winds, or the diurnal land and sea breeze. In the former case, the fog can drift in any time of day or night;

in the latter case the fog can come only in those hours that are normally the warmest, that is, the mid-day and afternoon hours, because it is at this time of day that the land and sea breeze is directed landwards.

Over the Gulf the fogs are of the winter type, and occur much more frequently than over nearby inland places. A large portion of the Gulf coast fogs can therefore be attributed to the influence of the Gulf. This influence evidences itself by fogs that form when winds blow from the Gulf toward the land that has been previously cooled by cold waves, and by fogs that form over the Gulf itself and are carried inland.

Table 9. Average Number of Days with Dense Fog at Selected Stations in the United States

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
Atlantic Coast													
Eastport, Me.	2	2	3	3	6	7	12	12	6	4	2	2	61
Portland, Me.	1	1	2	2	3	3	5	5	4	3	1	1	31
Nantucket, Mass.	4	4	6	5	8	9	11	8	6	3	2	2	68
New York, N. Y.	3	3	3	2	2	1	1	0	1	2	2	3	23
Philadelphia, Pa.	2	1	1	0	0	0	0	1	1	2	2	2	12
Atlantic City, N. J.	3	3	4	3	5	4	2	1	2	2	2	2	33
Washington, D. C.	2	1	1	1	0	0	0	0	1	2	2	2	12
Norfolk, Va.	2	2	1	0	1	1	0	0	1	2	1	2	13
Hatteras, N. C.	2	3	2	1	0	0	0	0	0	1	1	1	11
Wilmington, N. C.	2	1	1	1	0	0	0	0	1	2	1	2	11
Charleston, S. C.	4	3	2	2	0	0	0	0	1	1	2	3	18
Jacksonville, Fla.	4	2	1	1	0	0	0	0	0	1	2	3	14
Gulf Coast													
Key West, Fla.	0	0	0	0	0	0	0	0	0	0	0	0	0
Tampa, Fla.	4	3	2	1	0	0	0	0	0	1	2	4	17
Pensacola, Fla.	3	3	3	1	0	0	0	0	0	0	1	2	13
New Orleans, La.	4	2	3	1	0	0	0	0	0	1	3	2	16
Galveston, Tex.	6	4	5	1	0	0	0	0	0	0	2	3	21
Corpus Christi, Tex.	3	2	2	1	0	0	0	0	1	1	2	3	15
Pacific Coast													
Tatoosh I'ld, Wash.	0	1	1	1	3	4	8	11	8	5	1	1	44
Tacoma, Wash.	4	4	3	1	1	0	0	1	4	9	6	6	39
Eureka, Cal.	4	3	3	1	2	2	5	7	8	8	6	3	52
Point Reyes, Cal.	8	8	7	7	9	12	20	21	15	13	10	7	137
San Francisco, Cal.	3	2	1	1	1	1	1	2	2	2	3	3	22
Los Angeles, Cal.	1	2	2	2	2	3	3	3	4	3	2	1	28
San Diego, Cal.	2	3	1	1	1	1	1	1	2	4	3	1	21

"0" indicates either none, or less than one in two years.

TABLE 9 (*Continued*)

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
GREAT LAKES													
Duluth, Minn.	1	1	3	4	5	7	5	4	5	3	2	2	41
Marquette, Mich.	0	0	1	1	3	3	2	2	1	1	0	0	14
Sault Ste. Marie, Mich.	2	2	2	1	1	1	1	2	3	3	1	1	20
Escanaba, Mich.	2	1	2	2	2	1	1	2	2	2	1	1	19
Milwaukee, Wis.	1	1	1	1	2	2	1	1	1	2	1	2	16
Chicago, Ill.	1	2	1	1	0	0	0	0	1	0	0	1	7
Grand Haven, Mich.	1	1	1	1	2	1	1	1	1	1	1	1	13
Port Huron, Mich.	1	1	1	1	1	1	0	1	2	2	1	1	13
Detroit, Mich.	2	1	1	1	0	0	0	0	1	2	1	2	11
Toledo, Ohio	1	1	1	0	0	0	0	0	0	1	1	1	6
Cleveland, Ohio	1	1	1	1	0	0	0	0	0	0	1	1	6
Erie, Pa.	0	1	1	1	1	0	0	0	0	0	0	0	4
Buffalo, N. Y.	1	2	1	3	2	1	0	0	0	1	1	1	13
NORTHERN INTERIOR													
Charles City, Ia.	1	1	1	0	0	0	1	0	0	1	1	1	7
Cheyenne, Wyo.	1	1	1	2	1	1	0	1	1	1	0	0	10
Harrisburg, Pa.	1	1	1	1	1	1	1	1	1	1	1	1	12
Havre, Mont.	1	2	1	0	0	0	0	0	0	1	1	1	7
Indianapolis, Ind.	1	1	0	0	0	0	0	0	1	1	1	1	6
Keokuk, Ia.	1	1	1	0	0	0	0	0	0	1	1	2	7
Northfield, Vt.	0	0	0	0	0	0	1	1	2	2	0	0	6
Omaha, Neb.	1	1	1	0	0	0	0	0	1	1	1	1	7
Sheridan, Wyo.	0	1	0	0	0	0	0	0	1	1	1	1	4
Valentine, Neb.	0	0	1	1	1	0	0	1	1	1	0	1	7
Williston, N. D.	0	1	0	0	0	0	0	0	1	0	0	1	5
Winnemucca, Nev.	0	0	0	0	0	0	0	0	0	0	0	0	1
Yellowstone Park, Wyo.	0	0	0	0	0	0	0	0	0	0	0	0	1
SOUTHERN INTERIOR													
Cairo, Ill.	2	1	0	0	0	0	0	1	1	2	1	2	10
Charlotte, N. C.	3	2	1	0	0	0	0	1	1	1	2	3	14
Chattanooga, Tenn.	3	2	1	0	0	0	1	1	2	5	6	3	24
Dallas, Tex.	1	1	1	1	0	0	0	0	0	0	1	2	7
El Paso, Tex.	0	0	0	0	0	0	0	0	0	0	0	0	1
Fort Smith, Ark.	1	0	0	0	0	0	0	1	1	1	1	1	6
Independence, Cal.	0	0	0	0	0	0	0	0	0	0	0	0	1
Meridian, Miss.	1	1	1	0	0	0	0	0	0	1	1	1	6
Modena, Utah	1	1	0	0	0	0	0	0	0	0	0	1	3
Oklahoma City, Okla.	2	1	1	0	0	0	0	0	1	1	1	2	10
Phoenix, Ariz.	1	0	0	0	0	0	0	0	0	0	0	1	2
Sacramento, Cal.	5	2	1	0	0	0	0	0	0	1	3	6	18
Santa Fe, N. M.	1	0	0	0	0	0	0	0	0	0	0	1	3
Shreveport, La.	0	0	0	0	0	0	0	1	0	0	1	0	2
Taylor, Tex.	2	1	0	1	0	0	0	0	1	2	1	1	9

"0" indicates either none, or less than one in two years.

Contrasts in temperature over the Gulf waters are negligible in summer, but are marked in winter, much more so than over the Atlantic and Pacific in corresponding latitudes.

Fogs on the shores of the Great Lakes show a great diversity, both in annual frequency and in seasonal characteristics. Most places show the winter characteristic, indicating little Lake influence; in fact, there seems to be unmistakable evidence of a negative influence, that is, a fog preventative effect of the Lakes. This effect appears noticeable at Erie, Cleveland, and Chicago. These stations are affected by the Lakes only by winds that are in general northerly. In summer, northerly winds blow from the cool lakes to the warm land; in winter they originate over the still colder land areas to the north of the lakes; therefore, as already explained, cause clouds and precipitation, but rarely fogs. On still, clear nights in winter, gentle land and sea breeze effect sets in near the shore, causing a drainage of air in the lower levels toward the lake. This results in a subsidence of air that prevents radiation fogs which might otherwise occur, and that do occur farther inland. The general effect of the Lakes in winter is to cause a warming up of the windward shores. The net result is therefore a winter tendency to more clouds and less fog over a considerable portion of the shore lines than over regions farther inland.

On Lake Superior the summer characteristic is decidedly shown in the records of Duluth and Marquette. Owing to the greater expanse of this lake and its cold summer waters, the sea type of fog occurs frequently over its surface in the summer months, particularly with easterly and northeasterly winds. These winds carry the fog onshore. At Duluth, owing to its situation on a high ridge, fog is sometimes due to low clouds passing from the lake inland and enveloping the city. This in part explains the greater frequency of fog at Duluth as compared with Marquette. The secondary maximum at Duluth in September may be explained as fog formed on the cool land by relatively warm, moist air blowing from the lake. At this time of year the lake is still relatively warm, while the land is occasionally subject to cool periods, and

winds from an easterly quarter have passed over a long stretch of water.

A similar effect of lake fog blowing on the land is indicated in the average for Buffalo, which is greater than that for Erie and Cleveland. On Lake Erie this type of fog is quite likely to occur in spring, when the lake is still cold, and a warm westerly wind sweeping over the lake becomes befogged. In rare instances an abrupt change in wind to northerly will bring this fog to the south shore, where it soon dissipates over the warmer land.

The variation in fog frequency over inland places is based on differences in climate, altitude, topography, and other local influences, rather than on latitude. There appears to be no well-defined latitudinal variation, at least within the confines of continental United States. Owing to the usual location of Weather Bureau stations, the records therefrom do not often show the more local peculiarities of fog frequency; for example, the susceptibility of low places to radiation fog, the true frequency of fog in open country places unaffected by smoke and heat of cities, mountain fogs, etc.

A longitudinal and altitudinal influence is easily discernible in the data of Table 9, fogs increasing in frequency from west to east and from high to low places. The former variation is roughly parallel to the variation in general moisture as reflected in the statistics for average precipitation, although some exceptions are noted, as for example the relatively large frequency of fog in the Great Valley of California. The variation with altitude is based on figures for plateau and low land exposures, mountain fogs being entirely excluded. For all inland stations, the winter characteristic predominates.[5]

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[5] References for chapter: F. Entwistle, "Fog," *Journal of the Royal Aeronautical Society*, Vol. 31, pp. 342-384, May, 1928. Willis E. Hurd, "Fog at Sea." On back of several issues of Pilot Charts published by Hydrographic Office, U. S. Navy. H. Keaton, "Fog," *The Marine Observer*, May, 1929, pp. 106-109. G. I. Taylor, "Fog Conditions." *Aeronautical Journal*, Vol. 21, pp. 75-90, January-March, 1917. H. C. Willett, "Fog and Haze, their Causes, Distribution and Forecasting," *Monthly Weather Review*, Vol. 56, pp. 435-468, November, 1928. (See also section on "Fogs and Clouds," in Appendix 5.)

CHAPTER 6

CLOUDS

Formation. The process of cloud formation is the same as that of fogs, viz., condensation of the water vapor caused by cooling of the air below the dew-point. Fog, however, is a surface phenomenon, and the cooling is induced as a rule by radiation or by the mixture of air of different temperatures. Clouds, on the other hand, are upper air phenomena, though at times their bases lie very close to the surface. Radiation is not in any large sense a factor in their formation, but mixing of air of different temperatures is one of the agencies producing clouds. The most important and frequent cause is the cooling brought about by vertical convection, either thermal as on a hot afternoon, or mechanical as over a mountain ridge or by the gradual forced ascent of air above an underrunning current of relatively denser air, and by turbulence.

Types. Clouds are not classified, like fogs, according to their causes, but rather according to their form or appearance. The cloud types adopted by the International Conference of Directors of Meteorological Institutes and Observatories at Innsbruck in 1905, and their definitions as published in the International Cloud Atlas, second edition (Paris, 1910), are as follows:

1. **Cirrus** (Ci.). *Detached clouds of delicate and fibrous appearance, often showing a featherlike structure, generally of a whitish color.* Cirrus clouds take the most varied shapes, such as isolated tufts, thin filaments on a blue sky, threads spreading out in the form of feathers, curved filaments ending in tufts, sometimes called *Cirrus uncinus,* etc.; they are sometimes arranged in parallel belts which cross a portion of the sky in a great circle, and by an effect of perspective appear to converge toward a point on the horizon, or, if

sufficiently extended, toward the opposite point also. (Ci.-St. and Ci.-Cu., etc., are also sometimes arranged in similar bands.)

2. **Cirro-stratus** (Ci.-St.). *A thin, whitish sheet of clouds* sometimes covering the sky completely and giving it only a milky appearance (it is then called *Cirro-nebula*) at other times presenting, more or less distinctly, a formation like a tangled web. This sheet often produces halos around the sun and moon.

3. **Cirro-cumulus** (Ci.-Cu.), **Mackerel Sky.** *Small globular masses or white flakes without shadows, or showing very slight shadows, arranged in groups and often in lines.* [Small A.-Cu. may also be "Mackerel Sky."]

4. **Alto-stratus** (A.-St.). *A thick sheet of a gray or bluish color,* sometimes forming a compact mass of dark gray color and fibrous structure. At other times the sheet is thin, resembling thick Ci.-St., and through it the sun or the moon may be seen dimly gleaming as through ground glass. This form exhibits all changes peculiar to Ci.-St., but from measurements its average altitude is found to be about one-half that of Ci.-St. [Non-fibrous A.-St. is often undulated or festooned.]

5. **Alto-cumulus** (A.-Cu.). *Largish globular masses, white or grayish, partially shaded, arranged in groups or lines, and often so closely packed that their edges appear confused.* The detached masses are generally larger and more compact (resembling St.-Cu.) at the center of the group, but the thickness of the layer varies. At times the masses spread themselves out and assume the appearance of small waves or thin slightly curved plates. At the margin they form into finer flakes (resembling Ci.-Cu.) They often spread themselves out in lines in one or two directions.

6. **Strato-cumulus** (St.-Cu.). *Large globular masses or rolls of dark clouds often covering the whole sky, especially in winter.* Generally St.-Cu. presents the appearance of a gray layer irregularly broken up into masses of which the edge is often formed of smaller masses, often of wavy appearance resembling A.-Cu. Sometimes this cloud-form presents the characteristic appearance of great rolls arranged in parallel lines and pressed up against one another. In their centers these rolls are of a dark color. Blue sky may be seen through the intervening spaces, which are of a much lighter color. St.-Cu. clouds may be distinguished from Nb. by their globular or rolled appearance, and by the fact that they are not generally associated with rain.

7. Cumulus (Cu.), **Woolpack Clouds.** *Thick clouds of which the upper surface is domeshaped and exhibits protuberances while the base is horizontal.* These clouds appear to be formed by a diurnal ascensional movement which is almost always noticeable. When the cloud is opposite the sun, the surfaces facing the observer have a greater brilliance than the margins of the protuberances. When the light falls aslant, as is usually the case, these clouds throw deep shadows; when, on the contrary, the clouds are on the same side of the observer as the sun, they appear dark with bright edges.

True cumulus has well-defined upper and lower limits, but in strong winds a broken cloud resembling cumulus is often seen in which the detached portions undergo continual change. This form may be distinguished by the name *Fracto-cumulus* (Fr.-Cu.).

8. Cumulo-nimbus (Cu.-Nb.), the **Thunder Cloud; Shower Cloud.** *Heavy masses of cloud rising in the form of mountains, turrets, or anvils, generally surmounted by a sheet or screen of fibrous appearance* (*false cirrus*) *and having at its base a mass of cloud similar to nimbus.* From the base local showers of rain or snow (occasionally of hail or soft hail) usually fall. Sometimes the upper edges assume the compact form of cumulus, and form massive peaks around which delicate "false cirrus" floats. At other times the edges themselves separate into a fringe of filaments similar to cirrus clouds. This last form is particularly common in spring showers.

The front of thunderclouds of wide extent frequently presents the form of a large arc spread over a portion of a uniformly brighter sky.

9. Nimbus (Nb.), **Rain Clouds.** *A thick layer of dark clouds without shape and with ragged edges,* from which *steady* rain or snow usually falls. Through the openings in these clouds an upper layer of Ci.-St. or A.-St. may be seen almost invariably. If a layer of Nb. separates up in a strong wind into shreds, or if small loose clouds are visible floating underneath a large Nb., the cloud may be described as *Fracto-nimbus* (Fr.-Nb.) ("Scud" of sailors). [Note that all rain clouds are not nimbus (nor Cu.-Nb.), but only those having the characteristics as defined. A.-St., St., and St.-Cu. frequently yield rain or snow, while precipitation occasionally reaches the ground from A.-Cu., Cu., and possibly others.]

10. Stratus (St.). *A uniform layer of cloud resembling a fog but not resting on the ground.* When this sheet is broken up into irregular shreds in a wind, or by summits of mountains, it may be distinguished by the name *Fracto-stratus* (Fr.-St.). [St. may be

undulated or festooned, even though "uniform." Its evident low height (under 1,000 meters) distinguishes it from non-fibrous A.-St.]

Examples of these types are given in the accompanying plates, XXVII to XXXVI, inclusive. As a rule, a photograph of the sky shows, not a single well-defined type but a combina-

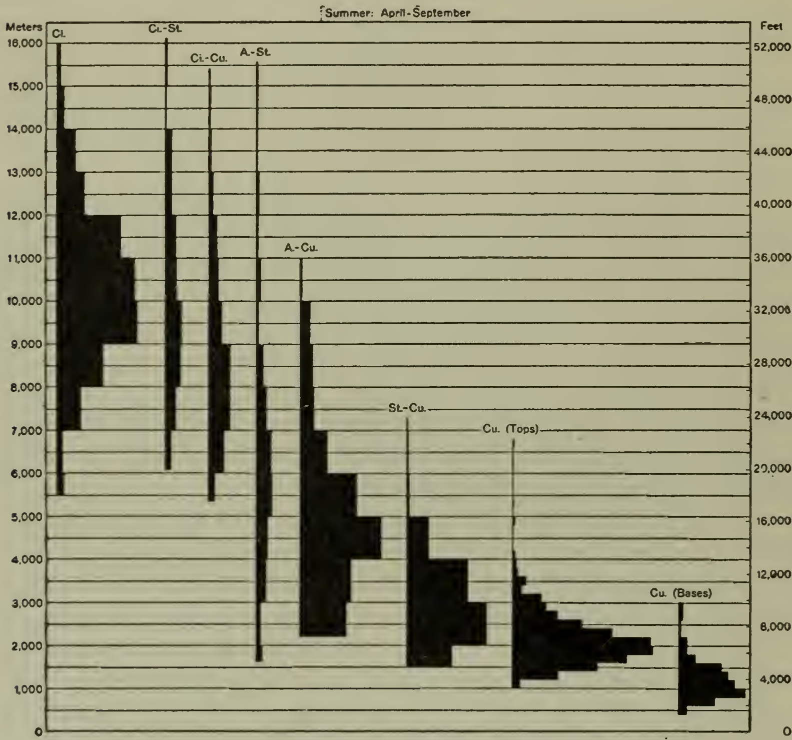


Figure 41. Cloud Height Frequencies, Washington, D. C., May to September, 1896, and April to June, 1897

Relative frequency at different heights indicated by width of figures. Ci., Ci.-St., Ci.-Cu., A.-St., A.-Cu., and St.-Cu. plotted on same width scale; Cu. (tops) plotted on one-half and Cu. (bases) on one-fifth the scale used in the other six groups.

tion of two or more types, one often merging into another, as for instance, cirrus into cirro-stratus, cumulus into cumulonimbus, etc. Cloud observing presents perhaps more difficulties than does that of any other element, and only the trained observer can identify some of the forms with accuracy.

Altitude. In general the cloud types occur within more or less definite limiting altitudes, although varying somewhat with direction of movement and also from place to place.[1] The classification may therefore be said to be in a rough way one of altitude as well as of appearance. A single exception

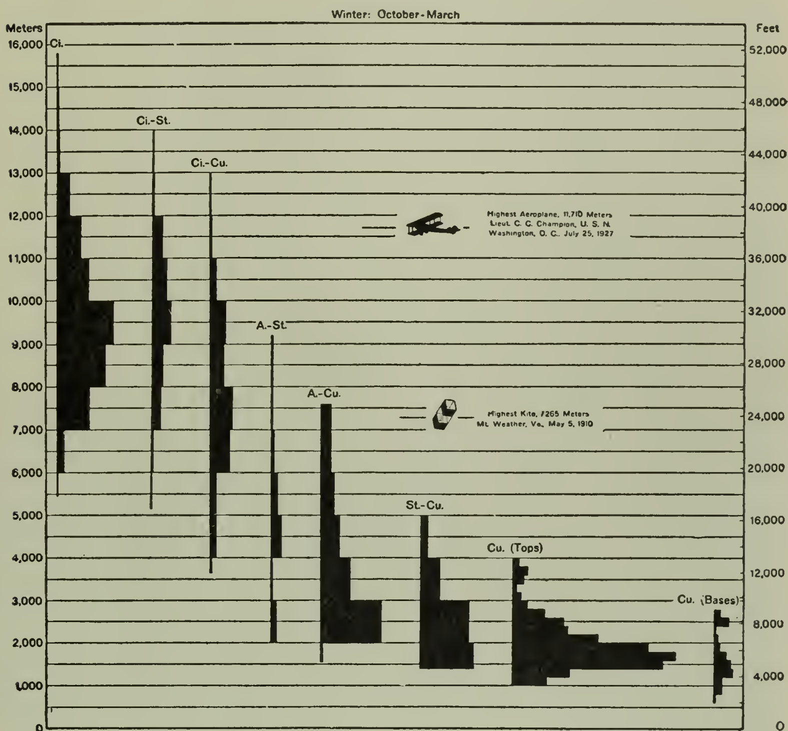


Figure 42. Cloud Height Frequencies, Washington, D. C., October, 1896, to March, 1897

Relative frequency at different heights indicated by width of figures. Ci., Ci.-St., Ci.-Cu., A.-St., A.-Cu., and St.-Cu. plotted on same width scale; Cu. (tops and bases) plotted on one-fifth the scale used in the other six groups.

is the alto-stratus type of cloud, which occurs over a wide range with no well-defined height of maximum frequency. In Figures 41 and 42 are presented the results of numerous

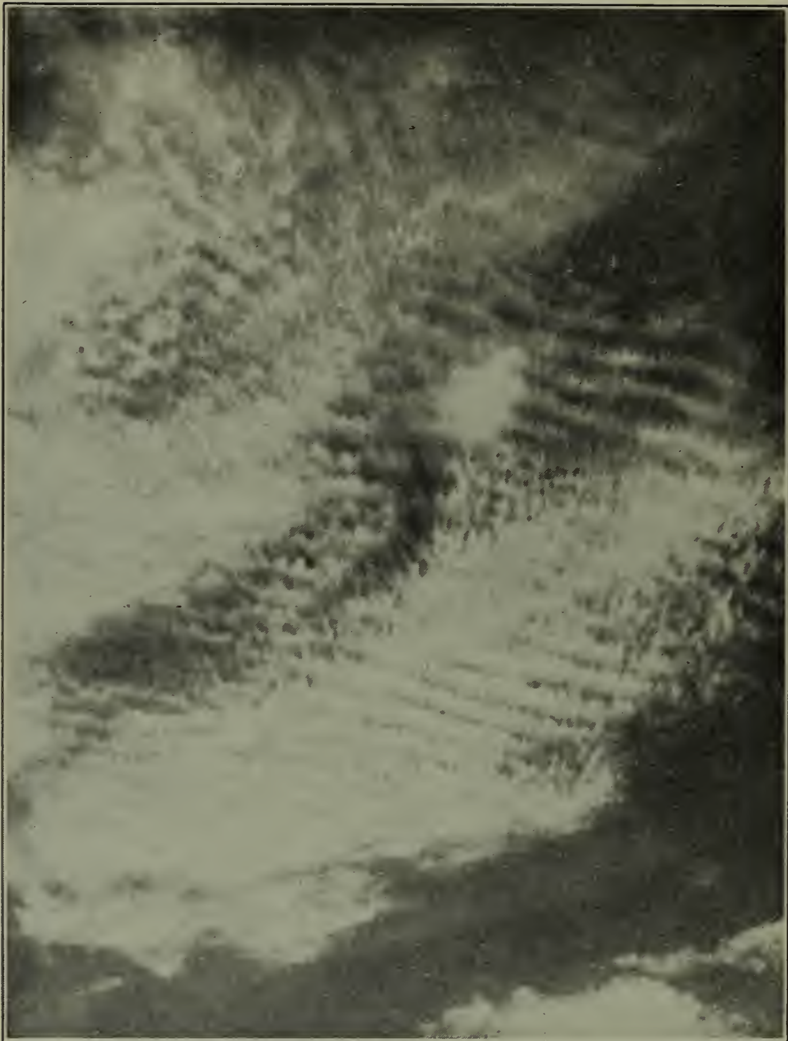
[1] *Cf.* Arthur F. Piippo, "Cloud Height According to Direction of Motion," *Monthly Weather Review*, Vol. 57, p. 154, April, 1929.

Mount Wilson, Calif. F. Ellerman

Plate XXVII. Cirrus, Tufted Form

Mount Weather, Va. A. J. Weed

Plate XXVIII. Cirrus (top half of picture) and Cirro-Stratus (bottom half)



Mount Wilson, Calif. E. E. Barnard

Plate XXIX. Cirro-Cumulus, Overhead

Orient, L. I., N. Y. W. S. Davis

Plate XXX. Cirro-Stratus and Fibrous Alto-Stratus Such as Originate from Thunderstorm Tops

Mount Weather, Va. A. J. Weed

Plate XXXI. Alto-Cumulus

Washington, D. C. W. J. Humphreys

Plate XXXII. Strato-Cumulus


Mount Wilson, Calif. F. Ellerman

Plate XXXIII. Nimbus, with Fog or Stratus Below

Topeka, Kan. W. M. Lyon

Plate XXXIV. Cumulus

Mount Wilson, Calif. F. Ellerman

Plate XXXV. Cumulo-Nimbus, Just Grown from Cumulus

Mount Weather, Va. A. J. Weed

Plate XXXVI. Stratus Clouds at Two Levels; One Practically on the Ground

measurements made at Washington, D. C.[2] It is to be noted that the higher clouds, particularly, occur over a large range of altitude, although there is a concentration of most of the occurrences within a much smaller range. The values shown diagrammatically in the figures may be briefly summarized.

Cirrus were measured 1,339 times. The height of maximum frequency, both summer and winter, was between 9,000 and 10,000 meters (30,000 and 33,000 ft.). Of the 846 summer measurements, 470 were above the 10,000-meter (33,000 ft.) level and 191 below the 9,000-meter (30,000 ft.) level, whereas of the 503 winter measurements, 166 were above and 207 below these respective levels. The mean summer level was 10,380 meters (34,000 ft.), mean winter level, 9,840 meters (32,000 ft.).

Cirro-stratus measurements numbered 189 in summer and 162 in winter. These clouds differed but little in height from the cirrus but were more uniformly distributed throughout the different levels.

Cirro-cumulus were measured 240 times in summer and 225 times in winter. The mean level of these clouds was slightly lower than that of the cirro-stratus.

Alto-stratus occurred throughout a great range of levels in summer but a moderate range in winter. The greatest frequency of occurrence in summer was between the levels of 5,000 and 7,000 meters (16,000 and 23,000 ft.); in winter, between those of 4,000 and 6,000 meters (13,000 and 20,000 ft.).

Alto-cumulus measurements were 690 in summer and 340 in winter. In the former season the greatest frequency of occurrence was found between the 4,000 and 5,000-meter (13,000 and 16,000 ft.) levels, while in the latter season it was found between the 2,000 and 3,000-meter (6,600 and 10,000 ft.) levels.

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[2] "Cloud Forms, According to the International System of Classification," 2d ed., Issued by U. S. Weather Bureau, Washington, 1928.

As in the case of the other cloud forms, the *strato-cumulus* and *cumulus* levels were found to be slightly higher in summer than in winter. The greatest frequency of occurrence of both these forms was found below the 3,000-meter (10,000 ft.) level. The cumulus tops exhibited a marked frequency at about 2,000 meters (6,600 ft.) in summer and 1,800 meters (5,900 ft.) in winter.

No separate classification of nimbus was made.

These figures are in good agreement with the results of similar investigations at Blue Hill, Mass.,[3] as will be noted from the following brief summary.

Cirrus were measured 227 times. The height of maximum frequency, both summer and winter, was between 8,000 and 8,400 meters (26,000 and 28,000 ft.). A secondary maximum frequency was found between 10,800 and 11,200 meters (35,000 and 37,000 ft.) for summer months and between 10,000 and 10,400 meters (33,000 and 34,000 ft.) for the winter months. Seven-tenths of all cirrus observed were found between 7,600 and 11,200 meters (25,000 and 37,000 ft.). Only three instances were found of cirrus above 13,000 meters (43,000 ft.).

Cirro-stratus. Summer measurements were made of 45 occurrences, of which one-third were between 10,000 and 10,800 meters (33,000 and 35,000 ft.) and the remainder mostly between 8,000 and 12,400 meters (26,000 and 41,000 ft.). Winter measurements of 58 occurrences showed that they are formed in lower levels than in summer, as they were found all the way from 4,400 to 12,000 meters (14,000 to 39,000 ft.) with a not very pronounced maximum frequency between 8,400 and 8,800 meters (28,000 to 29,000 ft.).

Cirro-cumulus, a form of relatively infrequent occurrence, were found 78 times. Four-tenths of these were between 6,000 and 7,200 meters (20,000 and 24,000 ft.), the remainder being found about equally above and below these levels.

[3] H. Helm Clayton, "Observations made at the Blue Hill Observatory," *Annals of the Astronomical Observatory of Harvard College*, Vol. 40, Part V, p. 253.

Alto-cumulus. One-half of those measured during the summer months, and two-thirds those of the winter months, were between 2,000 and 4,000 meters (6,600 and 13,000 ft.) with the maximum frequency for both summer and winter at 3,000 meters (10,000 ft.). For summer months, there was a secondary frequency maximum at 5,000 meters (16,000 ft.) with occasional occurrences up to 8,800 meters (29,000 ft.). For winter there was a secondary maximum at 6,400 meters (21,000 ft.) with none observed above that level.

Strato-cumulus, cumulus, and *nimbus* are comparatively near the ground, mostly below 2,000 meters (6,600 ft.) and seldom higher than 3,000 meters (10,000 ft.).

The rapid development, in recent years, of intensive weather service for commercial flying activities has added very substantially to the amount of data concerning heights of the lower cloud bases. This subject is discussed in greater detail in Chapter 7 on "Ceiling and Visibility."

Thickness. Not much is known as to average and extreme thickness of clouds, but from measurements with kites and captive balloons Peppler [4] gives the following results:

Stratus. Thickness less than 400 meters (1,300 ft.) in greatest number of cases; very seldom greater than 600 meters (2,000 ft.); mean thickness, 320 meters (1,000 ft.). There appears to be little seasonal difference.

Nimbus. Mean thickness, 800 meters (2,600 ft.). This is based on a smaller number of observations, owing to the fact that ascents are difficult when nimbus clouds prevail.

Cumulus. 89 observations gave a mean thickness of 500 meters (1,600 ft.).

Strato-cumulus. Layers less than 500 meters (1,600 ft.) in thickness were predominant; mean thickness, 310 meters (1,000 ft.).

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[4] W. Peppler, "Die vertikale Erstreckung der Wolkenschichten und die Wolkentagen über Lindenberg," *Meteorologische Zeitschrift*, January, 1921, pp. 18-21. Abstract by C. L. Meisinger in *Monthly Weather Review*, Vol. 49, pp. 347-348, June, 1921.

Alto-cumulus and alto-stratus. Mean thickness of A.-Cu., 120 meters (400 ft.). These last figures were based upon comparatively few observations, however. Hann in his "Lehrbuch der Meteorologie" gives 194 meters (600 ft.) for A.-Cu., and 510 meters (1,700 ft.) for A.-St.

Cumulo-nimbus clouds were apparently not included in this study. It is well known, though, that their thickness is much greater than is that of any other forms. Hann gives their average thickness as 2,070 meters (6,800 ft.) and their greatest measured thickness as above 4,600 meters (15,000 ft.). These figures are based on only 21 observations. As stated in the chapter on "Thunderstorms," cases have been reported in which the thickness of the Cu-Nb. exceeded 12 kilometers (8 miles).

Cloud velocity. Clouds travel as a rule at the speed of the air in which they happen to be. Hence, the average velocities of the different types of clouds are approximately the same as those of the winds at corresponding levels, as shown in Chapter 4 on "Winds."

There are some exceptions to the foregoing, namely, the so-called "stationary" or "standing" clouds. When air is forced over a mountain ridge a "crest" cloud often forms, parallel to the ridge and apparently stationary, notwithstanding that the air at the same level is moving rapidly. In reality, the cloud is forming on the windward side owing to condensation resulting from the forced ascent and cooling of the air, and dissipating on the leeward side because of evaporation incident to the descent and consequent warming of the air. A similar formation occurs in the case of isolated mountain peaks and clouds thus formed are called "banner" or "cap" clouds.

Clouds do not float. Clouds are composed of myriads of minute water droplets or ice spicules, depending on the temperature. The speed with which these particles fall is

exceedingly low, being of the order of 8 feet (2½ m.) per minute for the smallest drops. This low rate of fall gives the appearance of floating, and the delusion is strengthened by the fact that, in many cases, the droplets at the base of the cloud fall into warmer air and are evaporated. In addition, the presence of ascending currents often counteracts the tendency of the cloud particles to fall. *Therefore,* clouds do not float, in the strict sense of the word.

Formation of rain. The small droplets of water in a cloud are formed by condensation, on dust or other nuclei, of the water vapor in air that has been forced upward, by convection, topography, or convergence of different currents, to a height where it is cooled below its dew-point. These droplets, as previously stated, fall with reference to the air and in doing so they filter the air of its nuclei with the result that, as condensation proceeds, the water vapor has less and less nuclei on which to form and are therefore larger individually. In addition, many of the larger droplets coalesce and eventually become of sufficient size to fall at a rate exceeding the upward velocity of the air containing them.

Cloudiness in the United States. Figures 43 and 44, from Ward's "The Climates of the United States," show respectively the mean annual cloudiness and the average annual number of cloudy days. Although these charts are based on data for both high and low clouds, they are of interest in connection with the consideration of flight schedules and the extent to which their regularity can be guaranteed. There are two districts of maximum cloudiness: the extreme northwest and the lake region, the latter extending to northern New England. These sections are frequently under the influence of cyclonic disturbances and therefore have a larger number of rainy days than do other parts of the country. This is well brought out in Figure 45, also taken from Ward's "The Climates of the United States." The southwest is

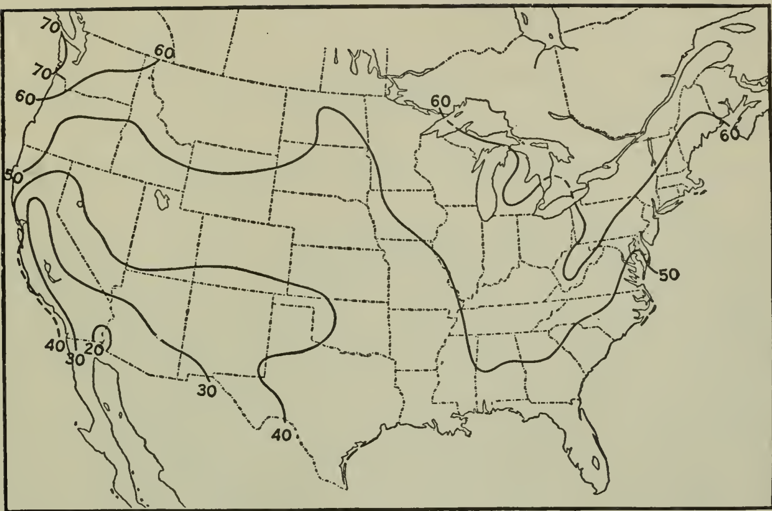

Figure 43. Average Annual Cloudiness (per cent) in the United States (after Ward)

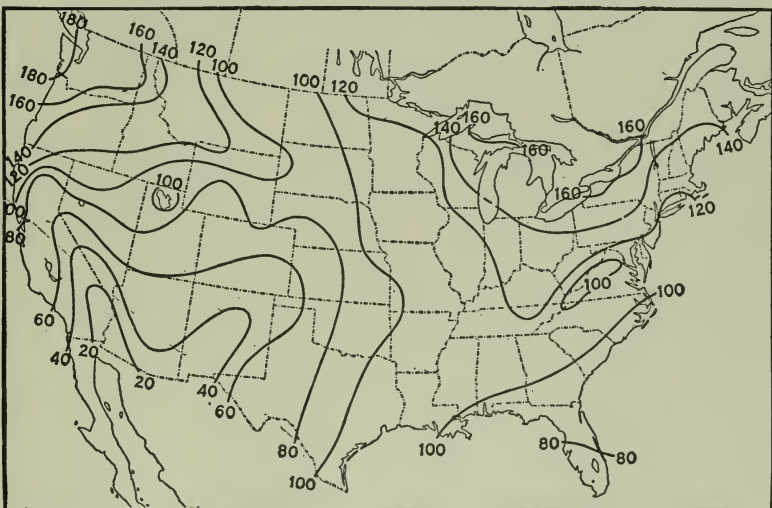

Figure 44. Average Annual Number of Cloudy Days in the United States (after Ward)

shown by the three charts to be noticeably free from both cloudiness and rainy days.

Diurnal variation. On the average there is a maximum cloudiness about noon and a minimum in the late evening.

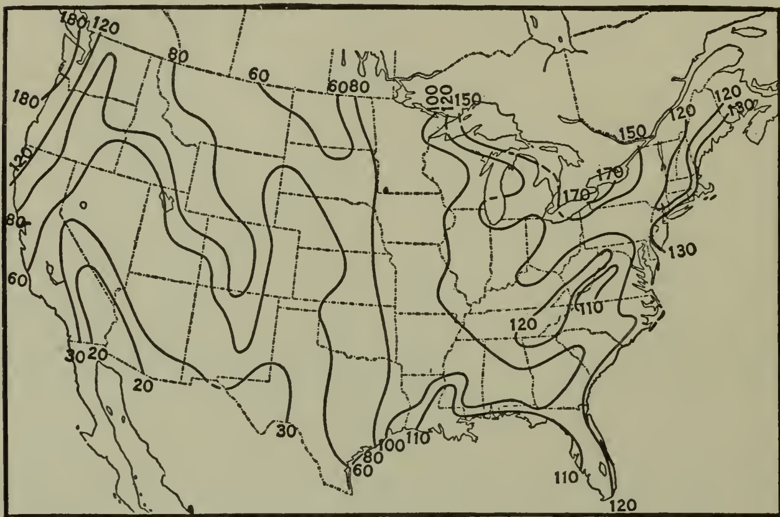

Figure 45. Average Annual Number of Rainy Days in the United States (after Ward)

Annual variation. In temperate latitudes maximum cloudiness occurs in the winter season, and minimum in the summer and early autumn. The variation is pronounced so far as the nights are concerned; it is less so in the daytime because of the frequency of clouds of the cumulus type during the summer.

CHAPTER 7

CEILING AND VISIBILITY

A few short years ago ceiling and visibility were scarcely given a thought in meteorology. Now they are among the most important working tools of the meteorologist whose duty it is to tell the pilot what the weather is and is going to be. It is proper, therefore, that they form the subject of a separate chapter in any work on *aeronautical* meteorology. It is proper also that both be considered in the one chapter, for they are often, though not always, quite closely related. Moreover and more important, they are frequently the determining factors in deciding whether or not a flight should be made. Nearly all pilots first ask, "What is the ceiling and the visibility?" Frequently they ask for nothing more.

It should be stated at the outset that the period during which these conditions have been systematically observed is not yet of sufficient length to yield data of high statistical value. Nevertheless, certain generalizations can be made which will probably hold true in the main, even after the number of observations is very materially increased.

Ceiling

Definition. As generally considered, ceiling is the height above which flying is not possible except in clouds. This means that the sky is overcast or very nearly overcast. When there are scattered or broken clouds, it is a simple matter to fly in the spaces or openings between them. In such cases the height of these clouds in no sense defines the ceiling. For example, the sky may be more than half covered with cumulus—a frequent condition in summer—and the bases of these

detached clouds may be, and usually are, of a nearly uniform height. It is incorrect, however, to call this height the ceiling. The true ceiling, in such cases, is the height of upper clouds

TABLE 10. AVERAGE SEASONAL AND ANNUAL FREQUENCY OF CEILINGS BELOW SELECTED HEIGHTS AT CERTAIN STATIONS

	Height m.	Height ft.	Spring %	Summer %	Autumn %	Winter %	Annual %
ROYAL CENTER, IND., 7 A.M.	150	500	5	2	6	11	6
	300	1,000	11	5	12	18	11
	500	1,600	18	8	17	27	17
	1,000	3,300	26	12	27	40	26
	1,500	4,900	31	16	31	46	31
ROYAL CENTER, IND., 2 P.M.	150	500	2	*0	2	5	2
	300	1,000	5	1	5	11	6
	500	1,600	13	2	11	23	12
	1,000	3,300	26	8	20	41	24
	1,500	4,900	34	18	28	46	32
DREXEL, NEB., 7 A.M.	150	500	6	5	5	7	6
	300	1,000	11	8	8	11	10
	500	1,600	17	11	12	17	14
	1,000	3,300	22	15	18	23	20
	1,500	4,900	25	18	20	27	23
DREXEL, NEB., 3 P.M.	150	500	1	1	2	3	2
	300	1,000	3	2	5	7	4
	500	1,600	8	4	8	14	8
	1,000	3,300	18	10	21	24	18
	1,500	4,900	25	17	21	27	22
BROKEN ARROW, OKLA., 7 A.M.	150	500	6	3	8	11	7
	300	1,000	9	4	11	16	10
	500	1,600	13	6	15	21	14
	1,000	3,300	22	9	19	27	19
	1,500	4,900	24	11	21	30	22
BROKEN ARROW, OKLA., 3 P.M.	150	500	2	1	2	5	2
	300	1,000	4	1	5	9	5
	500	1,600	8	2	9	15	9
	1,000	3,300	16	4	14	25	15
	1,500	4,900	22	9	17	26	19
GROESBECK, TEX., 7 A.M.	150	500	10	7	11	17	11
	300	1,000	13	9	14	21	14
	500	1,600	23	14	18	28	21
	1,000	3,300	32	16	23	38	27
	1,500	4,900	35	17	26	41	30
GROESBECK, TEX., 2 P.M.	150	500	2	*0	2	5	2
	300	1,000	3	1	3	8	4
	500	1,600	6	2	7	14	7
	1,000	3,300	14	5	13	24	14
	1,500	4,900	20	8	18	32	19

* Less than 0.5%.

above the openings, or if there are no such clouds the ceiling is recorded as unlimited. At the other end of the scale, zero ceiling occurs whenever there is dense fog or excessive precipitation, especially snow.

Relation to topography. In Chapter 6, some data are presented in Figures 41 and 42, and in the text regarding the measured heights of nearly all types of clouds. In practical flying there is very little interest concerning either the type of cloud or the height of upper clouds. All interest is centered in the height of clouds at levels near the surface. The critical height varies with topography. In level country a ceiling of 1,000 feet (300 m.) is ample. On an airway

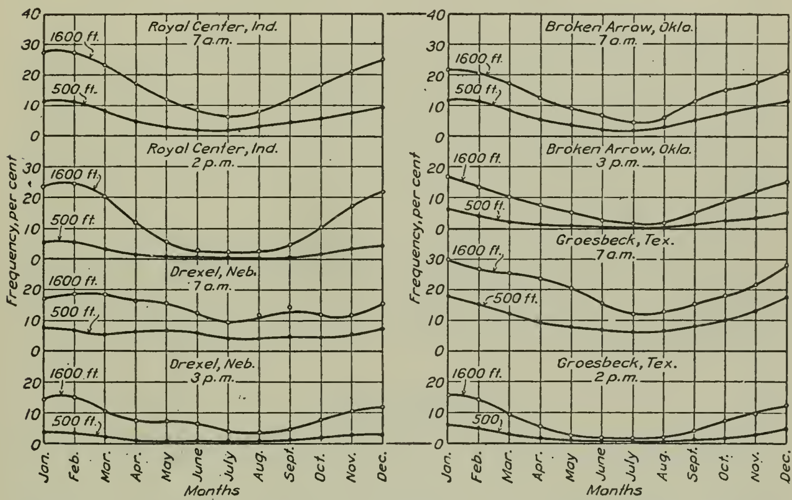

Figure 46. Annual Variation in Frequency of Ceilings Below 500 and 1,600 ft. (150 and 500 m.) in the Morning and Afternoon at Royal Center, Ind.; Drexel (near Omaha), Neb.; Broken Arrow, Okla.; and Groesbeck, Texas

where some hills rise to 1,500 feet (450 m.) above the valley floor, a ceiling of 2,000 feet (600 m.) is required for safe flying, assuming that it is desired to remain entirely out of the clouds. In very mountainous country the necessary ceilings are of course proportionately higher.

Annual and diurnal variation. For several years precise measurements of the ceiling have been made twice daily, 7 A.M. and 2 or 3 P.M., at pilot balloon stations in various parts of the United States. In Table 10 is presented a sum-

mary of the results obtained at four of the stations, located in the central portion of the country. The values give the frequency of occurrence of ceilings below certain selected heights. In order to visualize them to better advantage the frequencies for two of the heights, 500 and 1,600 feet (150 and 500 m.) are shown in Figure 46. These are the heights that ordinarily are of most interest.

The annual variation is well brought out in both the table and the curves, summer showing considerably less than half as many occurrences of low ceilings as winter.

There is also apparent a fairly pronounced diurnal variation in all seasons, low ceilings being about twice as frequent in early morning as in the afternoon, with an even greater difference than this for the lowest, that is, those of 500 feet (150 m.) or less.

Although the actual values undoubtedly differ from these considerably in other parts of the country, the general characteristics as to annual and diurnal variation are probably essentially the same.

Visibility

Definition. As used in meteorological observations and reports, visibility is the greatest distance from the observation point at which conspicuous objects such as trees, buildings, etc., can be seen and identified by the unaided eye. It is usually measured in a horizontal direction, although the subject of vertical visibility has received some attention also.

Horizontal visibility. In its regular system of observations the U. S. Weather Bureau reports horizontal visibility in accordance with a scale, adopted by the International Commission for Air Navigation. This scale follows, the English values being those given in Annex G of the "Convention Relating to the Regulation of Aerial Navigation."[1]

[1] See p. 60 of edition published in May, 1929.

Scale	Descriptive Terms	(meters)	Limiting distance (yards or miles)
0	Dense fog—prominent objects not visible at.....	50	55 yds.
1	Very bad—prominent objects not visible at.....	200	220 yds.
2	Bad—prominent objects not visible at..........	500	550 yds.
3	Very poor—prominent objects not visible at....	1,000	1,100 yds.
4	Poor—prominent objects not visible at.........	2,000	1¼ mi.
5	Indifferent—prominent objects not visible at....	4,000	2½ mi.
6	Fair—prominent objects not visible at.........	10,000	6¼ mi.
7	Good—prominent objects not visible at.........	20,000	12½ mi.
8	Very good—prominent objects not visible at....	50,000	31 mi.
9	Excellent—prominent objects visible beyond....	50,000	31 mi.

This scale is very convenient in transmitting reports in code, the proper visibility being sent by the one word, "zero," "one," "two," etc. In the Weather Bureau's airways service, however, the reports are usually transmitted by teletype or telephone and are therefore given, not in code, but in ordinary language. No standard scale is used, but the reports are given for the most part in miles or fractions thereof as follows: ⅛, ¼, ¾, 1, 1½, 2, 2½, 3, 4, 5, 6, and so on. Values less than ⅛ mile are expressed in feet to the nearest hundred.

In all cases, the limiting distances are laid off on a large-scale map and prominent objects are selected as points of reference, as nearly as possible at these distances. Some attempts have been made to devise apparatus for determining visibility more precisely, but thus far nothing really suitable has been developed.

Annual and diurnal variation. Table 11 and Figure 47 contain the results of measurements of visibility for the same places and periods as those in Table 10 and Figure 46 for ceilings. Very low visibilities are comparatively infrequent in this section of the country—the middle western states—those of less than 650 feet (200 m.), for example, occurring only about 1% or 2% of the time, with little seasonal, daily, or latitudinal variation. The higher visibilities, however, are most frequent in summer and least in winter, with spring and

autumn agreeing closely with each other and with the annual mean. Moreover, the data show considerably better visibility

TABLE 11. AVERAGE SEASONAL AND ANNUAL FREQUENCY OF VISIBILITY LESS THAN INDICATED DISTANCES AT CERTAIN STATIONS

	Visibility less than		Spring	Summer	Autumn	Winter	Annual
	m.	ft.	%	%	%	%	%
ROYAL CENTER, IND., 7 A.M.	200	650	2	1	2	4	2
	500	1,600	7	3	9	9	7
	1,000	3,300	11	5	13	17	12
	4,000	13,000	42	31	48	59	45
	7,000	23,000	79	71	80	90	80
ROYAL CENTER, IND., 2 P.M.	200	650	1	0	1	2	1
	500	1,600	4	1	5	7	4
	1,000	3,300	6	2	6	11	6
	4,000	13,000	20	8	16	33	19
	7,000	23,000	46	30	44	63	46
DREXEL, NEB., 7 A.M.	200	650	4	*0	2	6	3
	500	1,600	8	6	6	9	7
	1,000	3,300	13	10	10	14	12
	4,000	13,000	23	16	18	22	20
	7,000	23,000	44	39	42	44	42
DREXEL, NEB., 3 P.M.	200	650	1	0	1	4	1
	500	1,600	5	3	5	7	5
	1,000	3,300	6	4	6	10	7
	4,000	13,000	15	7	12	18	13
	7,000	23,000	38	29	36	42	36
BROKEN ARROW, OKLA., 7 A.M.	200	650	1	*0	2	2	1
	500	1,600	6	3	6	8	6
	1,000	3,300	10	5	11	16	11
	4,000	13,000	25	14	26	31	24
	7,000	23,000	53	43	59	65	55
BROKEN ARROW, OKLA., 3 P.M.	200	650	*0	0	*0	1	*0
	500	1,600	4	1	4	7	4
	1,000	3,300	5	1	5	10	5
	4,000	13,000	12	2	12	18	11
	7,000	23,000	34	15	28	43	30
GROESBECK, TEX., 7 A.M.	200	650	1	0	1	3	1
	500	1,600	4	1	4	8	4
	1,000	3,300	13	6	12	20	13
	4,000	13,000	16	8	15	24	16
	7,000	23,000	30	18	30	39	29
GROESBECK, TEX., 2 P.M.	200	650	*0	0	0	1	*0
	500	1,600	2	1	3	6	3
	1,000	3,300	3	1	3	9	4
	4,000	13,000	4	1	5	11	5
	7,000	23,000	12	7	10	19	12

* Less than 0.5%.

in the afternoon than in the early morning and in the southern than in the northern sections.

Relation to smoke, dust, etc. It should be borne in mind that the values shown in Table 11 and Figure 47 are repre-

sentative of conditions in the open country, a considerable distance from large industrial centers and therefore practically unaffected by smoke and other products of city factories. Visibility depends chiefly upon the amount of solid or liquid particles held in suspension by the air. Systematic measurements of the amount of solid matter contributed to

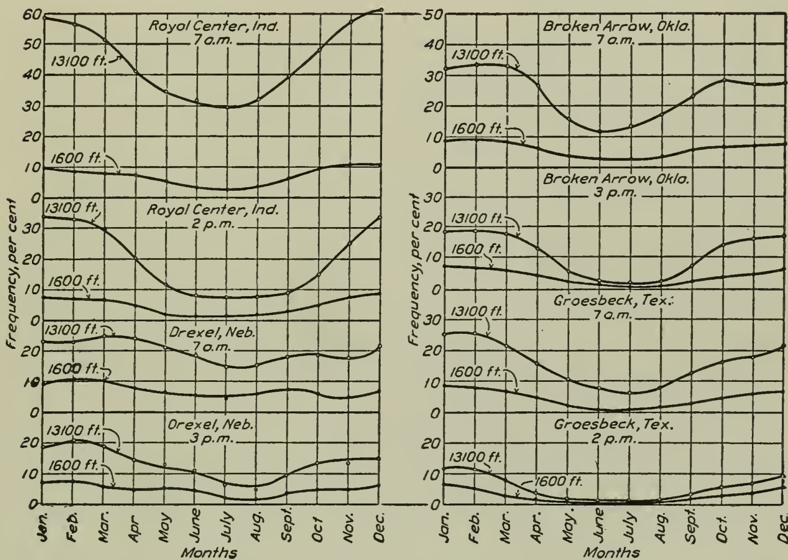

Figure 47. Annual Variation in Frequency of Visibilities Less Than 1,600 and 13,100 feet (500 and 4,000 m.) in the Morning and Afternoon at Royal Center, Ind.; Drexel (near Omaha), Neb.; Broken Arrow, Okla.; and Groesbeck, Texas

the atmosphere by smoke have been made at various places in this country and abroad, and yield startling figures. Measurements of the "sootfall" at Pittsburgh, before the evil there was mitigated, showed an average annual deposit amounting to 1,031 tons per square mile. London's average is 248 tons per square mile for the whole city and 426 tons per square mile in the central districts. In the heart of Glasgow the annual sootfall is 820 tons per square mile.

Other contributing factors in causing low visibility are dust and haze. In an "Investigation of the Dust Content of

the Atmosphere," [2] Kimball and Hand found that the visibility is roughly inversely proportional to the product of the number of dust particles per cubic centimeter and the relative humidity of the air. Thus unfortunately the poorest visibilities are on the average at points where there should be the best, namely, at terminal airports in or close to the larger centers of population.

Relation to various meteorological factors. The relationships between visibility and various other conditions have been the subject of several independent studies.[3] Eliminating those that are due to purely local influences, the results are in good agreement and may be briefly summarized as follows:

1. Best visibilities occur during the summer months and in the afternoon.
2. Days with convection are more likely to be accompanied by good visibility than are those without convection, and are extremely unlikely to be accompanied by very poor visibility.
3. The original source of the air, that is, air of polar or tropical origin, shows essentially no relationship, either at a coastal station or at one inland where industrial smoke is a factor. Of more importance appears to be the source of the air shortly before its arrival, as indicated by the wind direction. At Ellendale, N. Dak., westerly winds give the best visibilities; at Cranwell, Lincolnshire, winds from north to east.

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[2] H. H. Kimball and I. F. Hand, *Monthly Weather Review*, Vol. 52, pp. 133-141, March, 1924.

[3] References: Leslie A. Warren, "Horizontal Ground Day Visibility at Ellendale, N. Dak.," *Monthly Weather Review*, Vol. 54, pp. 420–423, October, 1926. W. H. Pick, and J. S. Farquharson, "Ground Day Visibility at Cranwell, Lincolnshire, in Relation to the Type of Air," *Quarterly Journal of the Royal Meteorological Society*, Vol. 53, pp. 293–294, July, 1927. W. H. Pick, "A Comparison between Surface Wind and Ground, Day Visibility at Cranwell, Lincolnshire, over the Four Years 1924 to 1927," *Quarterly Journal of the Royal Meteorological Society*, Vol. 54, pp. 134–136, April, 1928. W. H. Pick, and D. E. Davies, "Ground Horizontal Visibility at Valentia and the Type of Air Prevailing," *Quarterly Journal of the Royal Meteorological Society*, Vol. 55, pp. 81–82, January, 1929. W. H. Pick, "Ground Horizontal Visibility and Convection," *The Meteorological Magazine*, Vol. 62, pp. 289–290, January, 1928. H. L. Pace, "A Note on the Relationship between Visibility and Wind Direction and between Visibility and Wind Velocity at Holyhead," *Quarterly Journal of the Royal Meteorological Society*, Vol. 56, pp. 78–80, January, 1930. M. G. Bennett, "The Physical Conditions Controlling Visibility through the Atmosphere," *Quarterly Journal of the Royal Meteorological Society*, Vol. 56, pp. 1–29, January, 1930.

4. Visibility at inland stations improves steadily with wind velocity. Winds above 20 miles per hour (9 m.p.s.) are seldom accompanied by poor visibilities. At sea coast stations, however, the opposite relation holds for the higher velocities.
5. Low relative humidity is conducive to good visibility.
6. Visibility is higher in anticyclonic than in cyclonic weather.
7. In general, it is higher also in the interior than along coasts; in the direction from which a wind comes than in the opposite direction; and away from the sun than toward it.

Vertical visibility. It often happens that an airplane can be seen from the ground when the ground cannot be seen from the plane. Under these conditions the ground is covered by a thin haze, while the plane is in full sunshine. The top of this layer is called the "dust horizon." It is practically level, as a rule. This phenomenon occurs when there is sufficient dust in the lower air to differentiate it from the layer above by a well-marked boundary. Conditions are specially favorable when the surface layers are comparatively free from eddies. Such conditions often prevail in the early morning after a clear, quiet night with active radiation and resulting inversion layer not far above the surface.

Vertical visibility cannot, as a rule, be observed from the ground upward. A few investigations have been made, however, in which observations were made from airplanes.[4] The conclusions follow:

1. Surface visibility is a poor criterion of visibility at ordinary flying levels.
2. Visibility from the air is greatly diminished by clouds even in the incipient form.

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[4] Kimball and Hand, *loc cit.* W. H. Pick, and S. P. Peters, "A Note on the Vertical Visibility Estimated Looking Downward at Cranwell, Lincolnshire, during the Period February 1922, to June, 1923," *Quarterly Journal, Royal Meteorological Society*, Vol. 50, No. 209, pp. 53-59, January, 1924. W. H. Pick, and J. Paton, "Vertical Visibility and Convection," *The Meteorological Magazine*, Vol. 63, p. 236, November, 1928.

3. There is a progressive decrease in vertical visibility from low to high wind velocities, a relationship opposite to that for horizontal visibility.
4. Vertical visibility is distinctly better on days with convection than on days without convection. This, as shown previously, is true also for horizontal visibility.

Ceiling and visibility in different sections of the United States. As previously stated, ceiling and visibility have been regularly observed and recorded at numerous stations on or near established airways throughout the United States. Although the data are not as yet sufficient in amount to justify exact statistical treatment, they can be used as a basis for generalized statements. Summaries have accordingly been prepared, for different sections of the country, by meteorologists who have had the responsibility of organizing and providing intensive airways service for those sections. These summaries are presented in the following pages.

Northeastern States[5]

In the northeastern portion of the United States, a well-defined excess of cloudiness and low ceiling is found along the shores of the Great Lakes and southeastward over a large portion of the inland areas. Much of the region is mountainous, which is conducive to further cloud formation by mechanical raising of moving air masses. Bounded on one side by the Great Lakes, on the other by the Atlantic Ocean, much of this area has high humidity. Clouds form quickly and easily and they frequently persist for several days, with ceilings which are little more than 500 feet (150 m.) above average ground elevations.

Between the two sources of moisture lie the Appalachian ridges, which are frequently clouded, while areas on either side are almost clear. Such clouds are, of course, low with ceilings dangerously near the mountain tops. The best aver-

[5] By C. George Andrus. Weather Bureau Airport Station, Cleveland, Ohio.

age ceilings occur on the eastern flanks of the Blue Ridge where descending air is found with the prevailing westerly winds.

Besides the topography which tends to produce an abundance of low-ceiling weather, the drift toward the St. Lawrence valley of all Lows and their attendant areas of condensation is a favoring factor in producing low ceilings. The average Low has a low ceiling area around either its warm or cold front; sometimes along both.

Generally, high-pressure conditions are least likely to be accompanied by low ceiling, although one well-defined exception is the High which stagnates with its center over the mouth of the St. Lawrence. Other high-pressure conditions which result in low clouds are those of midwinter when cold air drifts across the warmer water over the Great Lakes.

A seasonal variation in low-ceiling conditions is well marked, especially in the Appalachian mountain regions and along the Great Lakes where the warmer seasons experience less and the colder more occurrences of low ceilings. Summer is as usual less subject to periods of low ceilings than is winter, over the whole area.

Low ceiling is especially important to air transport lines that operate across mountains because its presence may preclude flying over these mountains. Numerous cities, each with its encircling zone of air polluted by the products of combustion and manufacturing intensify the low-ceiling hazard at the airports in their vicinity and air pollution is therefore relatively higher in this section of the country than in any other.

Low ceiling in this area is dangerous in winter also because of its relation to ice accumulation on the planes, since it increases to a high degree the hazard involved in flying in the clouds. The low ceilings which attend line squalls and are sometimes obscured by violent rain and snowfalls have taken toll of several unwarned or unheeding pilots.

Use of dew-point data and careful study of their relation to the formation of low clouds are recommended as aids in predicting changes in ceiling. A rising dew-point when the interval is small between it and the dry temperature is a fairly reliable indication of lowering cloud masses, on the warmer sides of Lows.

Two peculiarities which occur occasionally are worth noting because of their danger. One is the tendency for two slightly separated horizontal cloud sheets to merge into one on the flanks of mountains. A pilot proceeding mountainward between the layers suddenly finds himself "pinched in." Mechanically induced vertical flow in the atmosphere near the mountains is the cause of this condition. The other peculiarity is the production of a fairly low ceiling by rain falling from clouds which may be more than several hundred feet high, sometimes in the alto-cumulus levels. This lower overcast develops first as scattered and wind-blown, low scud masses. These grow, if the rain continues and the ground is well soaked, until they attain solid formation of an additional sheet of cloud only a few hundred feet off the ground, with ragged and billowy lower edges.

Low visibility restricts flying operations more in the northeastern section of the country than in any other part of the United States. Several causes are involved which are highly developed or frequent in this quarter and are in general similar to the causes of low ceilings but also include many others, some man-made, which do not reduce ceiling. Some of these are on the increase.

Water vapor as an obstruction to vision is well identified with high humidity in air masses which have come across the Great Lakes or the Atlantic Ocean. Masses which have come inland from a long run over the sea and are not too briskly moved by the wind are more likely to produce fogs of wide extent than are those which have come inland after a short passage over the ocean and are moving at moderate or higher

velocities. Sunlight and wind as a general rule are the main preventives of fog and the strongest agents in its dispersion.

Visibility is reduced in this section by other sources which are more effective here than elsewhere because of their abundance. The pollution of the air by products of combustion and manufacturing is definitely high in this section, not merely in the immediate vicinity of the offending agents but for considerable areas around.

Thus, large cities as a rule are surrounded by areas of low visibility resulting from pollution. Industrial works of certain kinds discharge products which reduce visibility to less than 2 miles (3 km.) for a distance of 15 miles (24 km.) or more. The effect is direct and indirect. Directly, such a quantity of small particles is spread through the air that visibility is reduced. Indirectly these particles tend to assist in the suspension in the air of moisture particles which by themselves would present no great obstacle to vision. Oily or tarry substances hold moisture and resist the drying influence of sunshine, and as the products of combustion often consist of such substances this action commonly intensifies fogs. Hygroscopic chemicals are abundant in the vicinity of many manufacturing plants which discharge fumes into the air. Pollution is a growing factor, and measures toward its control and reduction are likely to be necessary in the near future.

Dust plays no great part in reducing visibility in this area. Drifting snow in windy weather during the winter is a cause for lowered visibility along the ground and results in a hazard to planes when landing, but is otherwise more apparent than real as a danger.

The worst obstruction to vision in the moisture class is fog. Fine rain is likewise a serious obstruction to vision. As a rule, with both moisture and other particles, the finer the particles the worse the visibility. A heavy rain with large drops does not hinder vision nearly as much as does one-tenth

the rainfall in the form of a drizzle. The densest fogs are those in which the droplets of moisture are exceedingly tiny.

Fog in the northeastern section of the country generally may be described as (1) valley, (2) mountain, (3) ocean, (4) snow or rain. Fog can frequently be ascribed to two or more of these conditions; often their origin and cause are more or less obscure because it is difficult to secure full information as to their exact extent.

Valley fogs are essentially phenomena due to radiation and air drainage. Their formation is best watched by assuming that they will form, unless inimical conditions are present, in any broad valley during the night hours. The longer the night the greater the chance and extent of fog. There is little chance for fog if at sunset the temperature and dew-point have a difference of 15° F. (8° C.) or more. Such fogs may fill the valleys by sunrise but usually "burn off" under rising temperatures during the first 4 hours of daylight. If, however, a sheet of high clouds comes in over these fogs their dispersion is greatly delayed.

Mountain fogs are strictly low cloud ceilings which envelop the higher points of the terrain. When the ceiling lifts, the fog seen as such by an observer on the mountain top disappears.

Ocean fogs occur on the coastal plain of the Atlantic seaboard and are frequenters of the southern and western sections of Highs which are located a short distance to the east of the Canadian and New England coasts. From local indications it is practicable to predict their occurrence by closely observing the wind direction and velocity and the temperature at stations on the coast. A desultory south or southeast wind whose temperature is normal or below in the daytime will often suddenly turn back to a chilly east or northeast light breeze at night and fog will attend this shift of wind. Once formed, such fogs are persistent and depend for their dispersion on a greatly altered pressure distribution, as it often happens that an incoming Low from the west will draw southerly to south-

westerly winds up over the top of the fog for several hours before it gradually wears away the upper surface of the fog and draws out the colder inversional temperature layer of foggy air.

Fog in the vicinity of the Great Lakes is less common but similar in production to the ocean fogs. It is easily formed when precipitation has occurred or is still occurring with winds which are light to calm, if the temperature of the water surfaces is above that of the land. In winter the lakes have ice and their temperature is therefore near freezing. At other seasons lake temperatures are normally colder than land temperatures and, therefore, the fog is slow to develop over the land.

Any widespread fog is the result of a widespread condition, hence slower to disperse than a local or limited one. On the other hand, during the evening or the period of development all fogs are likely to start as local phenomena and if the night is long the merging of several local fogs may result by sunrise. A winter fog usually is less mobile and more likely to stagnate than a summer fog, while the spring fogs are involved in cold surfaces and are often abnormally stagnant.

"Snow" fogs result when warm, moist air blows over snow-covered terrain. The reduction of the air temperature by the snow is the cause. If the snow is substantial enough to last under the influence of the warm air, fog will form. The farther to the windward the snow cover exists, the more likely is the fog to form at any specific point.

Rain in summer sometimes chills and wets the ground in a region to the extent that the lower strata of air are abnormally chilled while blowing very slowly over this region. Fog will result if the chilling is great or the moisture content of the air is high. Such fogs are usually transient, although if they occur in the early evening they may merge into valley fogs. Rising wind will disperse them quickly.

Southeastern States[6]

The southeastern portion of the United States lies south of the most frequented storm tracks. The storms that cause heavy rainfall in this region are southwestern Lows, including those that form in the Gulf of Mexico and those from the northwest that move far to the south before recurving. A considerable portion of the West Indian hurricanes pass inland on the Gulf coast or move up the Atlantic coast, causing widespread cloudiness, high winds and heavy precipitation. But these storms are confined mostly to late summer and autumn, and in most years, are not frequent enough seriously to affect flying.

This comparative freedom from storms, however, does not mean that the flying weather of the southeast is better than that of other sections. In fact, the topography of the region and the proximity of an abundant supply of heat and moisture from the Gulf of Mexico and the Atlantic combine to produce weather conditions that seriously interfere with flying at frequent intervals during a considerable part of the year.

The Appalachians, forming a high backbone between the Mississippi River and the Atlantic, are a decided topographic factor in determining ceiling and visibility. Even in fair weather a perpetual haze hangs over these mountains, as such names as Great Smoky and Blue Ridge suggest. This haze is sometimes so stratified as to resemble clouds, and the upper surface at 4,000 to 6,000 feet (1,200 to 1,800 m.) often furnishes a distinct horizon from above.

A notable instance of the effect of moist winds blowing across mountain ranges is found in northern Georgia and southwestern North Carolina. On the southern slope the rainfall increases from 50 and 55 inches (130 to 140 cm.) over the lower slopes to 60 and even 80 inches (150 to 200 cm.) a year on the higher slopes, while in the valleys beyond, the

[6] By John A. Riley, Weather Bureau Airport Station, Atlanta, Ga.

rainfall drops to less than 40 inches (100 cm.). The ridges of the southern Appalachians in Tennessee, Alabama, and Georgia seem to stretch out like fingers to grapple with the prevailing winds and squeeze out the moisture to form clouds, fog, and rainfall.

The Gulf of Mexico, as R. DeC. Ward points out,[7] is an important control of the climates east of the Rocky Mountains. It is a very warm body of water, and the most important source of moisture for the heavy rainfall of the southeast.

The Atlantic probably exercises an equally important control over flying conditions on the Atlantic seaboard and as far west as the Blue Ridge Mountains, easterly winds being definitely associated with low stratus clouds which are the most serious handicap to flying in this region. At Atlanta, for instance, the percentage of rain during the time the wind is northeast is five times higher than with northwest winds. Taking this value as unity for northeast winds the relative probability of rain for the other directions is as follows: N—0.31, NE—1.00, E—0.56, SE—0.59, S—0.32, SW—0.61, W—0.26, NW—0.17.[8]

High-pressure areas on the middle or north Atlantic coast constitute the controlling factor in the formation of low clouds over the east slope. A slow-moving High over New England, with an extension southwestward, and a moderate Low on the Gulf coast or in the Mississippi valley may be depended upon to produce a more or less extended period of low overcast.

The normal clockwise movement of the winds around the northeastern High causes the easterly surface winds to be overrun by moist southerly winds from the Gulf. The winds in this system, both at the surface and aloft, have a high vapor content and the relative humidity increases with falling temperature as the surface winds climb the slope from sea level,

[7] "The Climates of the United States."

[8] *Cf.* "The Rain-Bearing Winds at Atlanta, Ga.," by C. F. Von Herrmann, *Monthly Weather Review*, November, 1925.

across the Piedmont belt at 1,000 feet (300 m.), to 2,000 feet (600 m.) or more at the mountains. At the same time the southerly winds aloft are near the saturation point which may be passed as convergence causes further ascent and cooling.

The first clouds may form either near the ground or in the overrunning southerly winds, depending on the vertical distribution of temperature and humidity. When fully developed there may be four or five distinct cloud strata. Weather maps of February 7, 13, and 22, 1928, illustrate these conditions. Typical conditions occurred on September 13, 1929, when Air Mail pilot Sid Molloy lost his life at Atlanta, while attempting to fly underneath a very low overcast which touched the ground in places.

F. T. Cole, of the Weather Bureau Aerological Station at Due West, S. C., says that the most potent cause of low clouds from mid-November to mid-May is a strong Low to the southwest with a good pressure gradient. Lows that move to the north and east from the Gulf coast—Brownsville to Pensacola—bring low clouds about 12 hours ahead of the rain, and the rain is always accompanied by low clouds. But before low ceiling becomes a certainty the pressure must begin to fall: that is, the Low must really begin to move. Lows that come out of the east Gulf, he says, will bring low clouds at all seasons of the year if of any intensity. Lows that pass up the Atlantic coast in the autumn, October 1 to December 15, frequently bring threatening weather that apparently moves in from the east. If the movement of the Low is blocked, low ceiling with easterly winds may prevail for several days, but the clouds will be broken and the rainfall light.

Cole finds that temperature and humidity are of little forecast value, but that winds aloft are at times indicative of low clouds on the following day. A gradual change from east-southeast to south-southwest in a layer some 3,000 feet (900 m.) deep is almost a sure precursor of low ceiling and rain, but this does not hold true when the wind shifts abruptly.

A low overcast may occur when pressure gradients are insufficient to cause rainfall. Such conditions may prevail for several consecutive days and the weather then has a more or less regular diurnal sequence. Low clouds drift in between midnight and 3 or 4 A.M. and lift about 9 or 10 A.M. the following morning.

Moderately sharp temperature contrasts on the Jacksonville-Atlanta airway are often indicative of bad weather; they usually occur along the southeast margin of an incoming High. The low temperature within the high-pressure area and the high temperature to the south and east produce the well-known displacement of the center of low pressure toward the colder region, usually toward the northwest.[9] As a result of this displacement, the northerly surface winds are overrun by south and southwest winds, causing low clouds, rain, and poor visibility.

The period covered by the Air Mail service in the southeast is too short to show the seasonal trend of flying weather. Ceiling measurements covering 9 years at Due West, S. C., have been tabulated for this study by F. T. Cole. These figures show a steady decrease in frequency of low clouds from December to July, with a slight rise in August and September due to the hurricane season which reaches its height during this period, and then a drop to the July minimum in October.

Low clouds are rather common on summer mornings but they seldom last all day; the duration of low clouds is much greater in winter. Considerable variation in frequency of bad flying conditions occurs from year to year in every month. For instance, February, 1929, was probably the worst month since regular schedules began in this district, whereas February, 1930, was for the most part unusually fine.

Thunderstorms are the principal handicap to flying in summer; there are few warm days in summer when mail pilots

[9] See *Monthly Weather Review*, Supplement No. 21, "The Preparation and Significance of Free-Air Pressure Maps for the Central and Eastern United States," by C. L. Meisinger.

in this territory do not report seeing one or more; many times it is necessary to dodge one after another. It is not generally practicable to fly above them, but the pilot tries to pick out what appears to be the lightest or least active part of the storm.

Thunderstorms not only seriously reduce the ceiling and visibility while in progress, but the path of an afternoon or night thunderstorm is likely to be marked the following morning by ground fogs. On such nights temperature and dew-point readings are highly significant and are closely watched by experienced pilots. These fogs form within an hour or two after midnight and burn off soon after sunrise. Most of the inland fogs of summer are formed in this way; they are much more frequent than past records would indicate, for by 8 A.M., the time of the regular morning observation, summer fogs are entirely dissipated.

Over most of the southeast, except lower Florida, dense fogs occur on an average of 15 to 20 or more days a year; the greatest frequency is in the valleys of the middle and southern Appalachians, diminishing toward the west as well as toward the Atlantic and Gulf coasts.

The more widespread and persistent fogs accompany weak cyclonic movements, and their cause is similar to that of low stratus clouds previously discussed. Moist air transported by light southerly winds converging upon east and northeast winds from a High to the northeast brings the temperature and dew-point together to produce fog and perhaps misting rain. Such widespread fogs prevailed over much of the Mississippi valley and the southeast from December 8 to 15, 1929, with high pressure to the north and east and an indefinite low-pressure area from the lower Mississippi valley to the north Pacific coast.

The course of rivers is often marked by morning fogs; at Memphis it has been observed that after a warm period a shift of the wind to a northerly or westerly direction is likely to bring fog over the city from the river. A considerable

number of the winter fogs at Memphis do not begin until after 7 A.M., according to A. R. Long, Weather Bureau official at Memphis.

Coastal or marine fogs are most frequent where there are large temperature differences between the land and the water; they are therefore much less frequent along the Gulf and south Atlantic coasts than in New England. "Differences between land and water temperatures," says Professor H. C. Frankenfield, "are not so marked along the Atlantic and Gulf coasts as along the Great Lakes, and fog forms with nearly equal temperatures when the latter do not differ sufficiently to cause complete condensation in the form of rain or snow. Frequently rain will be falling at one place on the coast while at the next station, only a short distance away, there will be dense fog. It is usually observed, however, that at the place where the rain is falling the wind velocity is greater than where the fog prevails and a decrease in the velocity would doubtless be at once followed by dense fog."

Frankenfield gives the following seasonal percentages of dense fog for the south Atlantic coast: winter, 46; spring, 27; summer, 5; and autumn, 22. For the Gulf coast: winter, 54; spring, 30; summer, 1; and autumn, 15.[10] Along the Gulf coast the maximum frequency of fog is from the northwest coast of Florida to the northeast coast of Texas; the number of foggy days increasing toward the west. The greatest frequency is in January; scarcely any occur from June to September.

Weather conditions are described as very favorable for aviation in Florida by A. W. Brooks, Weather Bureau official at Miami Airport, who states that during the first year of operations, Air Mail failed to leave Miami on schedule only once—September 28, 1929, when a hurricane was passing through the Florida Straits into the Gulf of Mexico. Dense fogs are rare in southern Florida and are mostly shallow

[10] "Weather Forecasting in the United States," Ch. IX.

ground fogs which quickly disappear after sunrise. A solid overcast of low stratus or nimbus clouds is rare in southern Florida, Brooks states, except during a passing shower or when a hurricane is in the vicinity.

Central States[11]

The portion of the country considered in this section comprises those states or portions of states lying between about the 88th and 105th meridians, and extending from the Canadian boundary to the southern limits of the country, but not including the immediate Gulf coast.

Over this area, in common with other portions of the country, the average conditions of ceiling and visibility can be judged to a fair degree of accuracy by the general average amounts of precipitation. Ceiling and visibility are both controlled in large measure by the amount of moisture—both visible and invisible—contained in the air, while the moisture element is in turn roughly proportional to the average frequency and intensity of precipitation. We therefore find that there is a progressive improvement with respect to these conditions from east to west; slow at first, and then more rapid westward from about the 98th meridian, as the more arid regions of the Plains states are approached.

As regards visibility, another contributing factor to this graduation of average conditions from east to west is the general lessening in the amount of smoke from cities and industrial regions, parallel to the diminishing density of population westward. There is also an appreciable improvement in average visibility from north to south, this latitudinal difference, however, being confined to the colder months. As may be inferred, the southern states enjoy a relative infrequency of snowfalls, as compared with northern states, and snowfall, as is well known, diminishes visibility much more than rainfall. Moreover, the more pronounced changes in

[11] By Vincent E. Jakl, Weather Bureau Airport Station, Fort Crook (Omaha), Neb.

temperature and the precipitation that frequently attends such changes, to which northern states are subject, are conducive to greater frequencies in light to moderate fogs. Dense fogs are brought about by special conditions, as explained in Chapter 5; therefore we find that there is no important variation in this element with latitude, but a noticeable variation with longitude, i.e., greater frequency in dense fogs over eastern than over western sections on the average. The more general use of natural gas for heating in the southern states is perhaps not a negligible factor in bettering the conditions of visibility there as compared with northern states.

The advantage that the southern states enjoy is not really as great as might be apparent from the foregoing, as the favorable conditions mentioned are partly offset by low-pressure areas that first become evident as such in the southwest and pass northeastward. These southwestern Lows develop with northeastward progress, and cause widespread precipitation attended by low clouds and poor visibility. In their pronounced form they are peculiar to the colder months, and affect the middle and much of the southern portions of this area.

The western portions of the area likewise are affected by a condition peculiar to them that modifies the general statement that visibility always improves westward. These are the dust and sand storms that affect the arid regions, more particularly those of the southwest, and are most likely to occur in spring when the surface winds are on the average the strongest. The diminished visibility resulting from these storms is a factor to be reckoned with; nevertheless it is of far less importance than the products of moisture that are the chief cause of poor visibility over eastern sections.

A fair indication of relative weather conditions may be had from a comparison of the number of cloudy days over different portions. A cloudy day is one on which the average cloudiness was equal to eight-tenths or more of an overcast

sky. Over Minnesota and Wisconsin the average annual number is 130 to 150, while over the western Dakotas it is 80 to 100, and in the Plains region of Wyoming and Colorado, 60 to 70. In Iowa and eastern Nebraska, it is about 100, in Illinois and eastern Missouri and Arkansas, 110 to 120, while in northern and western Texas, from 30 to 50.

Over all the area low clouds are much more frequent and more prolonged in winter than in summer. Those in summer are largely in connection with thunderstorms, which are usually of short duration as compared with the overcast rainy or snowy conditions of winter. In winter, clouds that are low enough to be a hindrance to flying are usually associated with fogs, mists, snows, and other forms of low visibility.

The distinction must be made between the number of days on which unfavorable conditions of ceiling and visibility are recorded as occurring sometime during the day, and the number of days that they are persistent throughout the day, as in the former case a flight may merely be delayed, while in the latter it may have to be canceled for the day. The relation of the former to the latter is at least 2 to 1. The proportion is smaller in winter than in summer, that is, a poor condition is more likely to persist throughout the day in winter than in summer; it is also more likely to persist throughout the day over eastern sections of the district than over western sections.

In any generalization such as this, exception must be made of local peculiarities. For example, river valleys are more susceptible to radiation fogs than surrounding more elevated regions. On the other hand, over the more rugged portions of the country, places that rise quite high above their surroundings are subject to more frequent low ceilings.

For the area as a whole, it may be said that clouds lower than 1,000 feet (300 m.) occur on an average two or three times more often in winter than in summer, and probably twice as often at night and early morning as in the afternoon. They

are generally rare on summer afternoons, except as they occur in thunderstorms. From meager statistics available, an approximation may be made that over the eastern portion of the area, a condition of low clouds, or of dense fogs, or heavy rains or snows, is recorded as occurring some time within the 24 hours on probably 20% to 30% of the days in winter, while in summer the frequency may be about half that amount. Over the western portion, this frequency dwindles to perhaps half those figures for the western fringe of the area, possibly even less for the extreme southwestern portion. If we consider only those days on which unfavorable conditions persisted throughout the day, the number will diminish to not more than two or three days a month in the colder season, and to practically none in the summer months, even over the least favored sections in the east.

Visibility is better in summer than in winter, and better in the afternoon than at night or morning, probably averaging poorest in the early morning daylight hours when fogs and haze abound. Over the eastern portion of the area, visibility less than a third of a mile (0.5 km.) occurs on about 6% to 8% of the days on winter mornings, and about 3% of the days on summer mornings; on about 4% to 6% of the days on winter afternoons, and 1% to 2% of the summer afternoons. Visibility greater than 3 miles (5 km.) prevails during about 70% to 85% of the time. Over western sections, statistics if available would show a decidedly more favorable condition.

Rocky Mountain States[12]

Ceiling and visibility are perhaps of more importance to aviators in the Rocky Mountain region than in any other part of the country, owing to the fact that airways must traverse regions of great variation in elevation. Airplanes traversing a course over this region must pass over wide expanses of

[12] By Harry M. Hightman, Weather Bureau Airport Station, Salt Lake City, Utah.

rough, broken country, uninhabited desert areas, high mountain ranges, sometimes rising abruptly 4,000 feet (1,200 m.) or more above the general surface level, or through mountain passes, often narrow, with mountain peaks towering above in the near vicinity. Thus ceilings and visibilities that would be considered ample for flights in other parts of the country could not be considered at all for flights in this region.

On account of the great variation in surface elevations along the airways in this region, ceiling heights are very variable, and a determination of the average height along an airway would be of little value. However, it may be stated that the average height of ceilings in the Rocky Mountain region is greater than the average height in other parts of the country. At Salt Lake City, for example, it has been found that ceilings are seldom low enough to measure by means of a ceiling light, or ceiling balloons, that is, lower than 2,000 feet (600 m.), except when precipitation is occurring, or fog prevailing.

Ceilings low enough to interrupt airplane traffic are due almost invariably to low-lying clouds, or fog, in the higher mountain regions which obscure the mountain tops and close in the mountain passes. The most important and frequent causes limiting visibility are fogs, heavy snow, and floating frost in the air. The causes limiting visibility to a lesser extent are smoke, usually occurring in the vicinity of cities, dust storms, and occasionally blowing snow and heavy rain.

Low clouds in the Rocky Mountain region nearly always occur in connection with a Low or cyclone over or in the vicinity of this region. Often ceilings are high enough for flights in the lower valleys and comparatively level plateau regions, but too low to allow flights in the mountain region.

Fogs are almost wholly a winter-time phenomenon in the Rocky Mountain region. They are nearly always of the radiation type and form most frequently in the mountain valleys and over the plateau regions. They are more frequent and

extensive when the country is snow covered and an anticyclone has settled over the region. These fogs occasionally cover wide expanses of the country in the region surrounding Great Salt Lake, and sometimes continue without a break for a week or longer at one time. Their depth is usually not very great and it is often possible to fly over them.

Heavy snow, most frequently occurring in the mountain regions as snow squalls, is the next in importance to fog as an element limiting visibility. These squalls, usually local and limited in area, often set in suddenly in the mountain regions, blotting out passes and mountain sides, and are thus a serious menace to flying. They are one of the most difficult elements to deal with in airways forecasting in this region.

Frost in the air (floating frost crystals) usually occurring with fog formation, is not an infrequent occurrence in the Rocky Mountain region during periods of cold weather in winter, and sometimes materially restricts visibility. This phenomenon is often observed with a clear sky prevailing overhead, and with a temperature of 10° to 15° F. (−12° to −9° C.) or lower.

Smoke occasionally becomes dense enough during the winter months in the vicinity of the larger cities materially to restrict visibility, especially at night. A mixture of fog and smoke is a quite common occurrence in the vicinity of Salt Lake City during the winter months, and occasionally becomes dense enough to prevent landings and take-offs.

Dust storms occur occasionally over the desert regions, during dry periods of summer and autumn, when high winds prevail. Dust is sometimes lifted several thousand feet in the air and occasionally becomes dense enough to obscure landing fields.

There is very little interruption to flying owing to poor ceiling and poor visibility in the Rocky Mountain region during approximately 7 months of the year, that is, from May to November, inclusive. During May and November some

of the higher mountain passes may be closed in by low clouds during stormy periods, but this condition seldom lasts as long as a day at a time, and probably the average occurrence is less than three times during a month. From December to April, inclusive, conditions are very unfavorable for flying approximately one-sixth of the time. The three winter months, December, January, and February, are decidedly the worst.

Pacific Coast States[13]

Cloudiness along the Pacific coast is caused by three major meteorological processes and each process produces a separate type of ceiling. First, forced ascending currents of moist air over mountain ranges and in cyclonic circulations produce the greatest amount of cloudiness and the greatest variance in heights of ceiling. Since Washington and Oregon are nearer to the normal paths of storms entering the continent, the region from the Pacific Ocean to the Cascade Mountains and from extreme northern California to the Canadian border is the cloudiest on the Pacific Slope.

There are five mountain ranges averaging from 3,000 feet to 8,000 feet (900 to 2,400 m.) elevation lying across the airway between Los Angeles and Portland. The amount of cloudiness and ceiling heights over these mountain ranges depends upon the strength of the cyclonic winds of oceanic origin together with the proximity of the barometric depression. Ceilings are always higher over the valleys and lower in the mountains when cyclonic conditions produce cloudiness. A very general rule in estimating the degree of safety for a proposed flight over mountain ranges on the Pacific coast is as follows: with airway weather reports along the proposed flight showing varying amounts of cloudiness and heights of ceiling, and a weather map showing a cyclonic circulation bringing winds from the Pacific, the possibility of flight over the mountain ranges on the average is inversely proportional to the

[13] By Delbert M. Little, Weather Bureau Airport Station, Oakland, Cal.

pressure gradient. For example, under the above conditions a barometric pressure gradient of less than 0.10 inch in 300 miles (2.5 mm. in 500 km.) would indicate a flight could probably be made on schedule; a pressure gradient of from 0.10 to 0.20 inch in 300 miles (2.5 to 5 mm. in 500 km.) would indicate cautionary flying weather with a possibility of getting through; a pressure gradient of 0.20 to 0.30 inch in 300 miles (5 to 7.5 mm. in 500 km.) usually means impossible and dangerous flying weather.

The second process through which considerable cloudiness is produced on the Pacific coast is a radiation process and occurs mainly during the late spring, summer, and early autumn. During this period of the year the desert regions and interior valleys of California, frequently including the interior valleys of Oregon and Washington are heated through insolation during the summer days. The temperature in these valleys often exceeds 90° F. (32° C.) resulting in expansion of air over these areas producing a thermal cyclone[14] sometimes called a "heat-low." Cloudiness is seldom present over the area of the thermal cyclone, but cool, moist air from the Pacific Ocean flows inland over low ground, bays, inlets, and gaps in the coast hills. Ocean fog and low stratus clouds usually prevail over the ocean along the entire Pacific coast during this season. The movement of cool, moist air from the ocean to the land is attended by fog or stratus clouds moving inland but dissipating during the day as it underruns the heated inland air. All land areas from the coast to the mountain ranges near the coast, including all coastal valleys, bays, and inlets are thus filled with cool, moist ocean air which has forced the heated, dry inland air up to an elevation of from 1,500 feet to 4,000 feet (450 to 1,200 m.) above the surface. During the night the movement of ocean air inland gradually ceases. Both the warm, dry air mass aloft and to

[14] "The West Coast Atmospheric Fault," by Edward H. Bowie, *Monthly Weather Review*, August, 1929.

a greater extent the cool, moist air mass near the surface lose heat during the night due to radiation. Stratus clouds are formed by condensation beginning in the cool, moist layer of air near the elevation at which the warm, dry air overlies it. Numerous aerographic flights at San Diego by the Navy and eye observations while in flight over the San Francisco Bay area evidence the fact that the top of the stratus cloudiness along the coast is at the elevation where a rapid temperature inversion begins. Since cool, moist air movement from the ocean to the land is required, the most favorable pressure distribution for the air movement and resultant cloudiness is when isobars are parallel to the coast line. On the other hand, clear skies will prevail along the coast when a high-pressure area is pushing inland near the California-Oregon boundary and isobars are lying at such an angle with the coast that the air movement is practically parallel to it.

Surface humidities of 65% to 70% or greater during the late afternoon at coastal valley stations 10 or 12 miles (16 to 19 km.) inland are nearly always necessary for the general formation of the cloudiness in the coastal valleys. Ceiling heights vary from a few hundred feet to extremes of nearly 4,000 feet (1,200 m.) and the thickness of the layer of cloudiness varies from a few hundred feet to sometimes 3,000 feet (900 m.). Undoubtedly the height of ceiling depends upon the depth of the layer of cool, moist air moving in from the ocean. This is not easily determined from the surface but an examination of weather maps in relation to ceiling leads to the following general indications.[15] If the thermal cyclone over the interior is long and narrow, the depth of ocean air moving inland will be shallow and ceilings along the entire coast will be low, usually below 1,000 feet (300 m.). If the thermal cyclone spreads out over Nevada and southern Utah, ceilings along the California coast will be relatively high, 1,500 to 3,000 feet (450 to 900 m.), due to a deeper stratum

[15] Studies of George M. French, Weather Bureau Official at Los Angeles Airport.

of ocean air moving inland. If the northern end of the thermal cyclone is narrow and the southern end is wide, ceilings will be low along the northern California coast and high along the southern California coast. Skies over the interior valleys are usually clear at such times.

The third type of cloudiness or condensation is also a radiation phenomenon, but confined to the interior valleys of the Pacific coast region during the winter months. It is formed at the surface over interior valleys and the ordinarily relatively thin layer sometimes reaches an extreme thickness of nearly 4,000 feet (1,200 m.). An ideal condition for its formation is that following the passage of a cyclone southeastward through Oregon, Nevada, and southern Utah when a strong, high-pressure area develops in the rear of the storm over the Plateau region.

The interior valleys of California, Oregon, and Washington become filled with moist air during the passage of the storm and, after skies have cleared, outgoing radiation exceeds incoming radiation with a resulting net loss of heat. In this case temperature inversion is at the surface with radiation greatest near the ground; hence condensation begins at this level and proceeds upward. Because of the short days and long nights, insolation cannot overcome radiation and the fog continues to build up over the interior valleys for sometimes as much as 3 weeks at a time. The ceiling is usually on the ground during such periods, but often lifting during the middle of the day. A change in pressure distribution producing moderate to fresh upper air winds is required before the fog or condensation is driven out of the interior valleys by air movement.

Visibility in the Pacific coast region may be said to vary with the seasons, if restricted visibility due to fog or storms is not considered. During the late spring, summer, and early autumn, very little precipitation occurs over the entire area and upper air winds are usually light. Consequently the air

over the area from the Rocky Mountains westward accumulates haze and forest fire smoke during the season and is seldom washed out by rain or drifted away fast enough by air movement. If the season is unusually dry, forest fires are numerous and a smoky condition steadily increases as the season progresses. During the 1929 season, for example, visibility was reduced to ¼ mile (0.4 km.) over Washington and Oregon with smoke extending up to 10,000 feet (3,000 m.), resulting in suspension of much flying during a 2-weeks period in August of that year. A general rain over the district during such a period will clear the atmosphere and visibility will remain good for a week or ten days following. Strong northerly winds at moderate and high elevations will always clear the atmosphere and make visibility excellent for several days. During "north wind days" pilots have many times reported seeing Mount Rainier near Seattle, Washington, and Mount Shasta in northern California while flying at high elevations over central Oregon.

At times of marked temperature inversion there is an optical phenomenon known as a mirage, which affects the earthward visibility for a pilot flying above the inversion surface. It is more pronounced during the summer period and near the coast where the inversion is greatest. From the air it may be so pronounced as to have the appearance of a layer of fog, except that directly below the plane, ground objects can be faintly seen. From a point near the level where inversion begins, the top of the cool, moist layer has the appearance of a line on the horizon above which an apparent layer of exceptionally clear air about one degree wide prevails. This reflection phenomenon appears to the pilot during the daytime and disappears from him at night. Cities and airports not discernible at an angle from the plane during the day are readily seen under the same conditions at night and the false impression to the pilot is that smoke, haze, or fog has disappeared.

CHAPTER 8

THUNDERSTORMS

Of all the phenomena of the atmosphere there is none that excels the thunderstorm in beauty and majesty, as it builds up from small, detached cumuli into the towering and awe-inspiring cumulo-nimbus; none also that surpasses it as an example of the fury and violence which nature exhibits when she seeks to restore a state of balance which, by one cause or another or by several in combination, has been temporarily upset. Were it not for their destructiveness, thunderstorms would be among the most welcome of all the various manifestations of weather. They bring much needed relief after a sweltering day; they give to the earth copious rains in periods of drought; and, with their cauliflower heads and dazzling lightning displays, they are picturesque beyond description. But there are few who regard them with anything but dread, principally because of the startling suddenness of the lightning and the uncertainty as to when and where it may strike next. Fortunately to those who are on the ground there is little to fear from the wind, which at most seldom exceeds 50 to 60 miles an hour (22 to 27 m.p.s.). To those who are in the air, however, there is *much* to fear from this source. "Forewarned is forearmed." Every pilot should know what he has to deal with in order that he may avoid the particular dangers that thunderstorms present. Their chief features are discussed in the following paragraphs.

Formation. Thunderstorms are always the result of marked instability in the atmosphere. This instability may be caused (1) by different intensity of surface heating in adjacent regions; or (2) by the overrunning of warm, moist

air by much colder air, the latter forcing the former up to a level where cooling by adiabatic expansion results in condensation of its water vapor. These two types may be said to be thermally and mechanically produced, respectively.

The first case is the most common and is typical of hot, sultry, comparatively calm days in summer. Local heating here and there causes ascending currents of small area, each one surmounted by a cumulus, where the temperature of the rising air falls to a value at which the water vapor can no longer remain in invisible form but condenses into clouds. As the day advances, this local heating becomes more pronounced, the ascending currents increase in intensity and also in area, and finally many of them combine, as it were, into one principal upward current which forms at some place where the heating has been most vigorous. The small, detached cumuli have now merged into a black and towering cloud which in some cases has a relatively flat top, marking a warm layer beyond which this rising air cannot penetrate. Under such conditions the cloud spreads out laterally at top and bottom, giving the well-known, although by no means universal, anvil formation. Presently occasional flashes of lightning appear and these increase in frequency and intensity. We have now a fully developed thunderstorm of the local, or heat, type, but before analyzing its chief characteristics, let us return to a brief consideration of the formation of the mechanically produced type.

When a cyclonic storm passes to the north of a place a series of thunderstorms sometimes occurs along a line, as the cool and dry and therefore relatively heavy air brought by the northwesterly winds replaces the warm, moist, and therefore relatively light air of the southerly winds at the surface. This lighter air is pushed up to a level where condensation occurs, and if the action is sufficiently vigorous and sustained, we soon have a fully developed thunderstorm having characteristics similar to those of the local, heat variety but different in the

important respect that, instead of being isolated, it forms one of a series along a line (the "line squall"), sometimes hundreds of miles (or km.) in length, extending in a general southwesterly direction from the center of well-marked cyclones.

Thunderstorms resulting from the overrunning of the lower strata by air of decidedly lower potential temperature also occur quite frequently in some regions, even in the absence of any very active cyclonic development. Storms of this type are characteristic of the summer season in the central

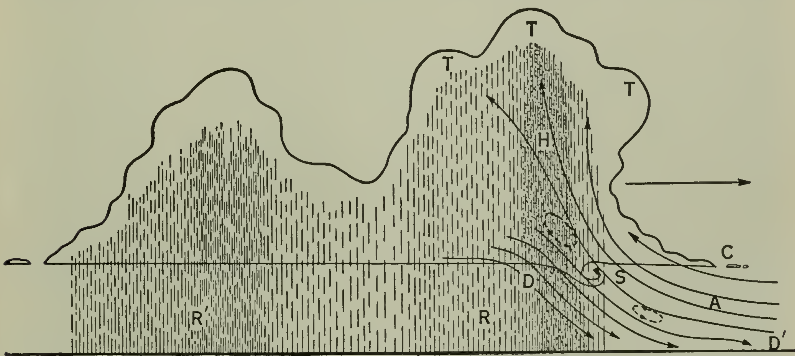

Figure 48. Ideal Cross-Section of a Typical Thunderstorm (after Humphreys)

A, ascending air; *D*, descending air; *C*, storm collar; *S*, roll scud; *D'*, wind gust; *H*, hail; *T*, thunderheads; *R*, primary rain; *R'*, secondary rain.

portions of the United States, particularly the Plains states, occurring there principally at night. They are also quite common over the oceans.

It is to be noted that rapid vertical convection of humid air, however induced, is the underlying cause of all thunderstorms and that, when formed, they have in general the same characteristics, some of which it will be worth our time to consider.

Figure 48 presents an idealized cross-section of a moving thunderstorm. Plates XXXVII to XXXIX show thunderstorms or parts of thunderstorms as they actually appear in nature.

Courtesy, E. Fontseré, "Atlas Élémentaire des Nuages"

Plate XXXVII. Cumulo-Nimbus, Anvil Type

Plate XXXVIII. Thunderstorm, Mount Weather, Va.

Courtesy, Bureau of Aeronautics, U. S. Navy

Plate XXXIX. Thunderstorm at Pensacola, Fla.

Vertical movements. As indicated by the arrows in Figure 48, nearly all of the air entering the cloud does so through its front undersurface. The area or cross-section of the ascending currents is very small compared with the size of the entire storm. But the small size is fully compensated by the vigorous upward velocity. From theoretical considerations, based on the size of hailstones, it is known that ascending currents with speeds of approximately 100 miles an hour (45 m.p.s.) sometimes occur. Such speeds are required to sustain hailstones 3 inches (76 mm.) in diameter; stones of this size have been authentically reported (and photographed) on many occasions. Larger stones have been reported, but their occurrence is questionable. However, assuming that they do occur, a velocity in the neighborhood of 200 miles an hour (90 m.p.s.) would be required for a diameter of 4 to 5 inches (100 to 125 mm.). For 1 and 2 inches (25 and 50 mm.) the necessary velocities are about 50 and 75 miles an hour (22 and 34 m.p.s.).[1]

Again reverting to Figure 48, it will be noted that the most active descent of air takes place just behind the ascending air. The rate of descent is, however, very much lower, as a rule at any rate, than that of ascent. A balance must, of course, be maintained and this is accomplished by a general, gradual descent of air throughout the greater portion of the thunderstorm back of the small area at the front, marked in the figure by the upward and downward pointing arrows.

The vertical movements, as described in the foregoing paragraphs, are those that are generally found in moving thunderstorms. If a storm is stationary, or nearly so, the central portion consists of descending currents and around this central portion is a ring-shaped belt of rising air. This type of storm is seldom very violent and tends, if it continues stationary, to spread laterally, resolving itself in some cases

[1] W. J. Humphreys, "The Uprush of Air Necessary to Sustain the Hailstone," *Monthly Weather Review*, Vol. 56, p. 314, August, 1928.

into a series of small thunderstorms along the periphery of the original storm.

Wind gust or squall wind. One of the most characteristic features of thunderstorms is the wind gust, shown in Figure 48 at *D′*. It is caused by the outrushing air of the descending current and at times attains a fairly high velocity, 50 to 60 miles per hour (22 to 27 m.p.s.), but its duration as a rule is brief. If the ground is dry, the advent of the wind gust is usually heralded by a dust cloud; otherwise there is practically no advance warning, except the apparent distance of the storm cloud from the observer.

Squall cloud. At the interface of the ascending warm current and the descending cool current, in the front of the storm, there is considerable turbulence, most of which is invisible. Near the front lower edge of the cumulo-nimbus, however, condensation of the water vapor in the ascending air occurs as shown at *S* in Figure 48. The direction of motion of this cloud is counterclockwise, around a horizontal axis, as is also that of invisible vortices in this turbulent region nearer the surface.

A test of the existence of rolling motion in the squall cloud was purposely made by David L. Webster[2] in a Curtiss JN4H, just as a thunderstorm was getting well started. He says: "This expectation (of rolling motion in the cloud) was not only confirmed, but confirmed to such an unexpected extent that the strain on the wings caused them to creak with a scream audible even through the roar of the motor. I promptly brought the machine up into a stall, to reduce the strain by reducing the air speed, and dropped out of the cloud rolling with all the angular velocity that the most ardent upholder of this theory of thunderstorms could wish for.

"The conclusion is that the theory is confirmed as far as such observation can confirm it, but that the experiment

[2] "The Squall Cloud in a Thunderstorm: A Direct Observation of Its Motion," *Monthly Weather Review*, Vol. 52, p. 586, December, 1924.

Huntington, W. Va. W. J. Humphreys

Plate XL. Storm Collar in Front of Thunderstorm

shares one characteristic with the famous thunderstorm experiment of Benjamin Franklin, namely, that its repetition is most decidedly inadvisable."

Storm collar. In many thunderstorms the base at the front reaches forward, so to speak, a short distance in advance of the main cloud and forming a part of it. This is called the storm collar. Its position is shown at *C* in Figure 48 and a good idea of its appearance is presented in Plate XL.

Mammato-cumulus. This cloud seldom occurs in the well-developed formation as shown by Plate XLI, except in connection with severe thunderstorms. When seen in front of a storm, it may be accepted as an indication of an unusually violent one, with possibly tornadoes nearby. A very fine display of this type of cloud was observed at St. Louis 2 to 3 hours before the tornado of May 27, 1896, struck that city.[3] Other similar cases have been reported.

As a rule, however, this cloud is seen in the rear of thunderstorms where it seems to be caused by the downthrust or settling of the cold, snow-filled air which is spreading out laterally at the tops of the cumulo-nimbus.[4]

Lightning. The rate of fall of raindrops varies with their diameter, but experiments show that when the diameter increases, by coalescence of smaller droplets, to more than about 0.2 inch (5 mm.), the drops become unstable and break up. The rate of fall of the drops just before becoming unstable, is about 18 miles per hour (8 m.p.s.), and this is the fastest rate possible for raindrops.

Experiments have shown also that the breaking up of the drops gives rise to a difference of electric potential between the raindrops and the surrounding air, the former having a positive and the latter a negative charge.

As has been stated previously, the warm, humid air at

[3] H. C. Frankenfield, "The Tornado of May 27, 1896, at St. Louis, Mo.," *Monthly Weather Review*, Vol. 34, pp. 77-81, March, 1896.

[4] C. F. Brooks, "Types of Mammato-Cumulus Clouds," *Monthly Weather Review*, Vol. 47 No. 6, pp. 398-400, June, 1919.

Ashland, Ky. W. J. Humphreys

Plate XLI. Mammato-Cumulus

the front of the storm ascends, or rather is forced up, at a high velocity, greatly exceeding the maximum rate, 18 miles per hour (8 m.p.s.) at which the largest raindrops can fall. This means that large quantities of water are trapped, so to speak, by this ascending current and are carried upward at enormous velocities, the drops being broken up, reunited, and broken up again and again, during which process the electric potential difference becomes so large that lightning discharges are necessary to relieve the tension. These discharges take place largely, probably almost wholly, between different parts of the cloud mass, but a few of them are from cloud to earth and very rarely from earth to cloud.

Rain gush. Frequently a sudden and heavy downpour of rain occurs soon after a sharp clap of thunder, the latter being heard some seconds after a vivid lightning flash. As a matter of fact, the lightning, thunder, and rainfall all occur at the same instant. In the violent turmoil of the cloud mass there is at times a sudden increase in the rate of condensation of moisture and the resulting increase in the number of drops present sets off a lightning discharge, which of course produces the thunder. The intervals between the times when an observer notes the lightning, thunder, and gush of rain are owing entirely to their different rates of travel—lightning, 186,000 miles per second (nearly 300,000 km./sec.); thunder, 1,100 feet per second (335 m.p.s.); and rain, about 20 to 25 feet per second (6 to 8 m.p.s.).

Hail. When the drops of water are carried by the violent ascending currents into strata in which the temperature is below the freezing point, they become ice pellets. Later, in falling, they become coated with water some of which immediately freezes owing to the cold nucleus. If again carried upward to subfreezing levels, another layer of ice is formed, and so on. The size of the hailstones becomes very large in some cases. It must depend, of course, upon the strength

of the vertical currents. Hail is formed only where these are very active, that is, in the front portion of the storm, shown at *H* in Figure 48.

It is worth noting that the hail and also the cold rain accentuate the descent of air in the central portions of thunderstorms. This tendency is in part owing to the evaporation and melting of the water and hail, respectively, and therefore the cooling of the air through which they fall, also in part to viscosity, since in falling they literally drag the air along with them.

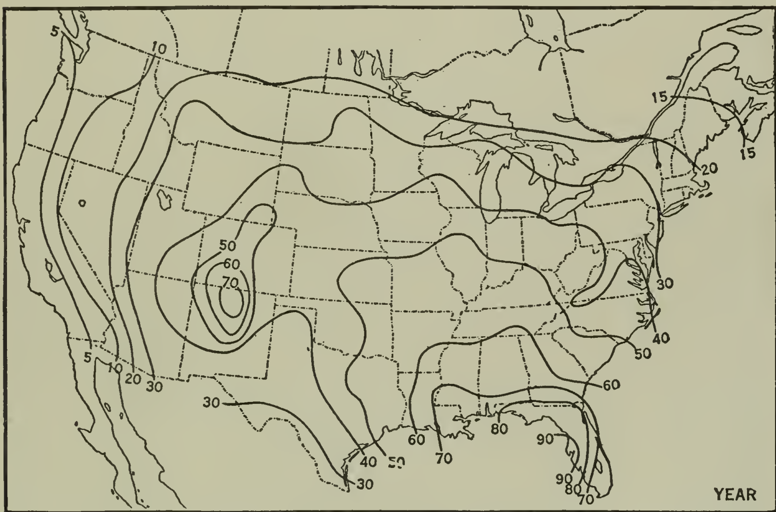

Figure 49. Average Annual Number of Days with Thunderstorms in the United States (after Alexander)

Annual variation. Thunderstorms of the local or heat type occur almost altogether in the summer; those of the cyclonic or line squall type are most numerous then, but may occur at any season. The average monthly and annual number of days with thunderstorms at selected stations in the United States, based on a 20-year record, is given in Table 12.

Distribution in the United States. Figure 49 shows the average annual number of days with thunderstorms, based

Table 12. Average Number of Days with Thunderstorms at Selected Stations in the United States

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
Amarillo, Tex......	*	*	1	3	6	7	7	7	5	2	*	*	38
Asheville, N. C.....	*	1	2	4	7	13	13	11	5	1	*	*	57
Atlanta, Ga........	*	1	3	4	7	10	15	12	5	1	1	1	60
Birmingham, Ala...	1	2	4	5	7	12	15	12	7	1	1	1	68
Bismarck, N. Dak..	0	0	*	1	4	7	8	6	3	1	*	0	30
Boise, Idaho........	*	*	1	1	3	4	4	3	2	1	*	*	19
Boston, Mass......	*	*	1	1	2	3	5	4	2	1	*	*	19
Burlington, Vt......	*	*	1	1	4	6	8	6	3	1	*	*	30
Charleston, S. C....	1	2	2	4	6	9	14	12	7	1	1	*	59
Cheyenne, Wyo.....	0	0	*	3	7	11	14	12	5	1	0	0	53
Chicago, Ill........	*	*	3	3	5	8	7	7	5	2	1	*	41
Columbus, Ohio....	1	1	3	4	6	9	10	8	4	1	1	*	48
Denver, Colo.......	0	0	1	2	6	10	12	12	5	1	*	0	49
Detroit, Mich......	*	1	2	3	5	7	7	6	4	2	1	*	38
Dubuque, Ia........	*	*	2	3	6	8	7	7	5	2	1	*	41
Duluth, Minn......	*	0	*	1	4	6	8	6	3	1	*	0	29
El Paso, Tex.......	*	*	*	1	2	5	9	9	4	2	1	*	33
Fort Worth, Tex....	2	2	4	7	9	8	6	7	5	3	1	1	55
Galveston, Tex.....	1	2	2	4	6	5	8	8	7	3	2	2	50
Helena, Mont......	*	0	*	1	4	9	10	8	3	1	*	*	36
Huron, S. Dak.....	0	*	1	2	5	9	8	7	4	1	*	0	37
Indianapolis, Ind...	*	1	3	5	6	9	9	7	5	2	2	*	49
Jacksonville, Fla....	1	2	3	4	9	13	19	17	9	2	*	1	80
Kansas City, Mo...	1	1	4	5	8	10	10	9	7	3	1	*	59
Key West, Fla......	1	1	1	3	5	9	11	12	11	4	1	2	61
Lexington, Ky......	1	1	3	4	7	10	11	8	5	1	1	1	53
Los Angeles, Cal....	1	*	1	*	*	*	*	*	*	*	*	*	4
Memphis, Tenn.....	1	2	4	6	6	8	9	8	4	2	2	1	53
Modena, Utah.....	*	*	1	2	3	3	12	12	4	1	*	*	38
Nashville, Tenn....	1	2	4	5	7	10	11	9	5	2	1	1	58
New Orleans, La....	2	2	4	5	7	11	15	15	8	2	1	2	74
New York, N. Y...	*	*	1	2	4	6	8	6	3	1	*	*	31
Norfolk, Va........	*	1	1	3	6	8	9	8	3	1	*	*	40
North Platte, Neb..	0	*	*	2	7	9	10	9	3	1	*	0	41
OklahomaCity,Okla.	1	1	3	5	7	9	6	7	5	3	1	*	48
Omaha, Neb........	*	*	1	4	8	9	9	9	6	2	1	*	49
Pensacola, Fla......	2	3	3	5	8	12	16	16	10	3	1	2	81
Philadelphia, Pa....	*	1	1	2	4	6	9	6	3	1	*	*	33
Phoenix, Ariz.......	*	1	1	1	1	1	10	10	3	1	1	*	30
Pittsburgh, Pa......	*	1	2	4	6	9	10	8	5	1	*	*	46
Portland, Me.......	*	0	*	*	2	3	4	4	2	1	*	*	16
Reno, Nev.........	0	*	*	*	2	3	4	3	2	1	0	0	15
Richmond, Va......	*	*	2	3	6	8	10	8	4	1	*	*	42
Roseburg, Ore......	0	0	*	*	1	1	1	1	*	*	0	*	4
St. Louis, Mo......	*	1	4	5	7	8	8	8	5	3	1	*	50
Salt Lake City,Utah	1	*	1	2	4	5	7	8	4	3	*	*	35
San Antonio, Tex...	*	1	3	5	7	4	5	4	5	2	1	1	38
San Diego, Cal.....	*	*	*	*	*	*	*	1	*	*	*	*	3
San Francisco, Cal..	*	*	*	*	0	*	*	0	*	*	*	*	2
Santa Fe, N. Mex...	*	*	2	3	7	11	21	18	8	3	*	*	73
Sault Ste. Marie, Mich............	*	0	1	1	2	4	4	4	3	2	*	0	21
Savannah, Ga......	1	1	2	4	7	10	15	13	6	1	*	*	60
Seattle, Wash......	*	*	*	*	1	1	1	1	1	1	*	*	6
Syracuse, N. Y.....	*	*	1	2	4	7	8	6	4	2	*	*	34
Tampa, Fla........	1	2	2	3	9	16	22	21	13	3	1	1	94
Washington, D. C...	*	1	2	3	5	8	9	7	4	1	*	*	40
Wichita, Kans......	*	1	2	5	8	9	9	8	6	3	1	*	52
Wilmington, N. C...	1	1	2	4	5	8	12	11	5	1	*	*	50
Winnemucca, Nev..	0	0	*	1	2	3	3	2	2	*	*	0	13

* Less than 1 day in 2 years, on the average.

Note: Numbers indicate days with storms rather than the total number of storms, two or more of which sometimes occur in a single day.

upon a 20-year record[5] for all observing stations, including those listed in Table 12. Conspicuous features are the small number along the Pacific coast and the center of maximum frequency in the Florida peninsula, with a secondary maximum at Santa Fe, N. Mex.

It should be noted that the values in Table 12 and in Figure 49 represent the number of *days* with thunderstorms rather than the total number of thunderstorms. Several storms, in some cases 5 or 6, occur in a single day. These data, that is, the total number of storms, again based on a 20-year period, are given in the last column of Table 13. The stations are the same as those included in Table 12. The differences in the annual values are large only in the case of places in the southern part of the United States, where heat or local storms predominate.

Diurnal variation.[6] Table 13 also shows the percentage frequency of thunderstorms in 3-hourly groups, for different parts of the day. These data have been further combined into 6-hourly and 12-hourly groups and are presented in Figures 50 to 55.

To one accustomed to thinking that thunderstorms over land areas occur principally in mid-afternoon (and most meteorological treatises either make that statement or give the inference), these charts come as something of a surprise. Figure 52 shows that less than 50% occur during this period over more than half the United States, including most of the northeastern and all of the midwestern states; the extreme northwest and southwest, and a narrow strip along the Pacific coast. With the exception of the last-named section, all of these areas are of continental type. The most conspicuous feature of this map is the large area in the central portion.

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[5] William H. Alexander, "The Distribution of Thunderstorms in the United States," *Monthly Weather Review*, Vol. 52, June, 1924. A notable contribution on the subject of thunderstorm distribution has recently been published by C. E. P. Brooks on "The Distribution of Thunderstorms over the Globe," Meteorological Office, London, M. O. 254d. London, 1925.

[6] Largely based on a manuscript paper by the author, entitled "The Diurnal Variation of Thunderstorms in the United States."

TABLE 13. ANNUAL PERCENTAGE FREQUENCY OF THUNDERSTORMS BETWEEN 12 AND 3 A.M.; 3 AND 6 A.M., ETC.; ALSO AVERAGE ANNUAL NUMBER OF THUNDERSTORMS

Station	A.M.				P.M.				Annual Total
	12–3	3–6	6–9	9–12	12–3	3–6	6–9	9–12	
Amarillo, Tex.	6	5	3	3	16	28	22	17	38
Asheville, N. C.	3	3	2	6	42	29	11	4	57
Atlanta, Ga.	3	3	3	12	32	30	13	4	61
Birmingham, Ala.	5	6	5	14	31	23	11	5	77
Bismarck, N. Dak.	8	10	9	8	13	21	18	13	34
Boise, Idaho	6	7	2	6	18	28	24	9	22
Boston, Mass.	8	7	5	5	20	27	19	9	20
Burlington, Vt.	6	4	5	12	28	23	15	7	36
Charleston, S. C.	5	6	6	11	29	22	14	7	62
Cheyenne, Wyo.	1	1	1	8	40	29	15	5	58
Chicago, Ill.	11	10	8	7	18	16	17	13	46
Columbus, Ohio	8	9	6	10	20	21	16	10	57
Denver, Colo.	2	1	2	4	35	32	20	4	51
Detroit, Mich.	9	7	6	9	20	21	17	11	42
Dubuque, Iowa	11	14	11	8	14	17	15	10	45
Duluth, Minn.	11	9	6	8	20	15	17	14	36
El Paso, Tex.	4	3	1	3	20	32	25	12	36
Fort Worth, Tex.	10	10	7	8	21	19	14	11	55
Galveston, Tex.	10	15	17	13	19	10	10	6	51
Helena, Mont.	3	3	3	9	30	30	17	5	48
Huron, S. Dak.	12	10	9	6	9	19	19	16	40
Indianapolis, Ind.	9	7	6	11	21	24	13	9	58
Jacksonville, Fla.	2	2	2	18	36	27	10	3	101
Kansas City, Mo.	14	15	7	6	10	17	17	14	66
Key West, Fla.	6	7	13	15	17	19	14	9	72
Lexington, Ky.	6	8	6	10	25	21	16	8	59
Los Angeles, Cal.	15	10	6	14	26	16	9	4	4
Memphis, Tenn.	5	7	9	10	22	23	16	8	58
Modena, Utah	4	2	4	15	36	27	11	1	49
Nashville, Tenn.	7	7	6	9	25	24	14	8	67
New Orleans, La.	4	5	4	21	34	18	9	5	79
New York, N. Y.	8	4	3	5	21	24	21	14	36
Norfolk, Va.	5	5	1	7	25	28	19	10	44
North Platte, Neb.	8	8	4	6	10	21	26	17	44
Oklahoma City, Okla.	12	11	12	6	17	17	16	9	54
Omaha, Neb.	14	12	9	6	10	17	18	14	54
Pensacola, Fla.	6	9	11	16	26	17	9	6	97
Philadelphia, Pa.	8	3	4	5	17	27	22	14	35
Phoenix, Ariz.	8	8	7	5	8	21	30	13	32
Pittsburgh, Pa.	6	5	6	7	22	25	20	9	56
Portland, Me.	11	4	3	8	23	27	16	8	16
Reno, Nev.	1	*	*	11	39	36	11	2	17
Richmond, Va.	5	4	2	4	21	30	23	11	44
Roseburg, Ore.	9	5	3	4	20	36	15	8	5
St. Louis, Mo.	9	10	8	10	20	16	17	10	55
Salt Lake City, Utah	5	7	4	13	27	23	14	7	40
San Antonio, Tex.	9	9	5	7	17	21	20	12	38
San Diego, Cal.	13	10	15	12	12	15	11	12	3
San Francisco, Cal.	11	22	9	16	15	6	3	18	2
Santa Fe, N. Mex.	*	*	3	18	38	26	12	3	83
Sault Ste. Marie, Mich.	12	9	9	12	18	14	16	10	21
Savannah, Ga.	4	2	4	8	31	29	14	8	64
Seattle, Wash.	4	4	2	10	24	24	22	10	6
Syracuse, N. Y.	8	4	6	8	23	24	18	9	44
Tampa, Fla.	2	3	5	11	27	34	14	4	107
Washington, D. C.	6	5	3	4	18	31	21	12	44
Wichita, Kans.	14	14	10	7	13	15	14	13	56
Wilmington, N. C.	7	8	4	10	26	19	15	11	58
Winnemucca, Nev.	3	1	2	11	41	28	10	4	14

* Less than 1%.

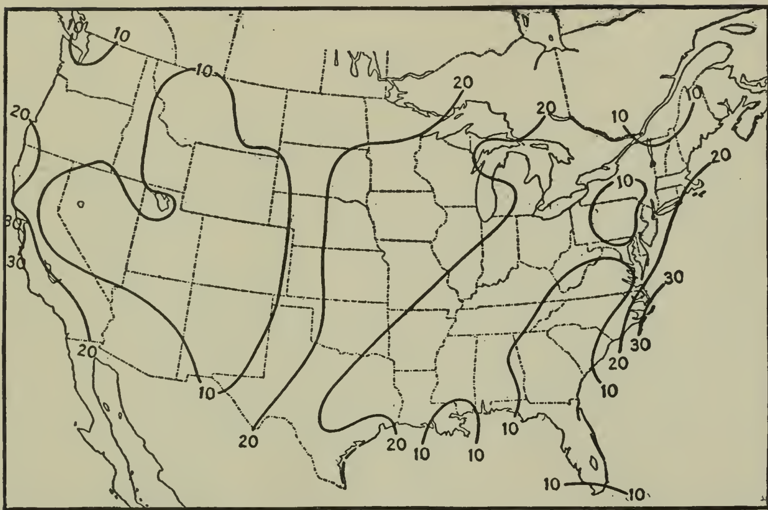

Figure 50. Average Percentage Frequency of Thunderstorms from Midnight to 6 A.M., in the United States

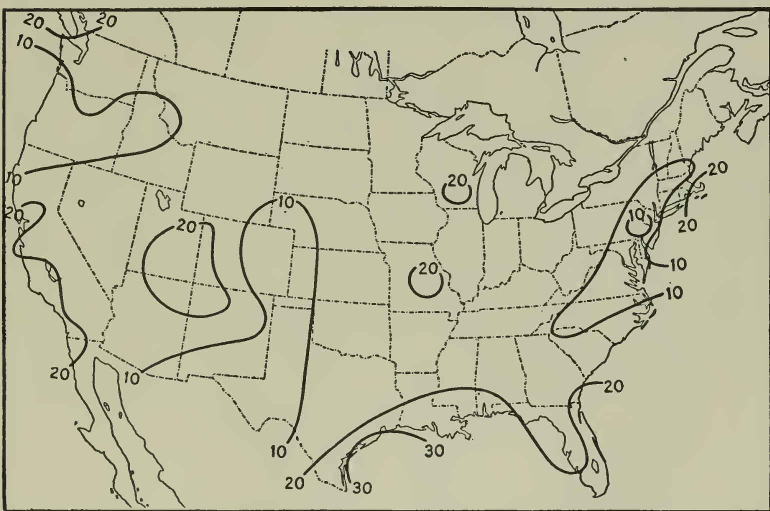

Figure 51. Average Percentage Frequency of Thunderstorms from 6 A.M. to Noon, in the United States

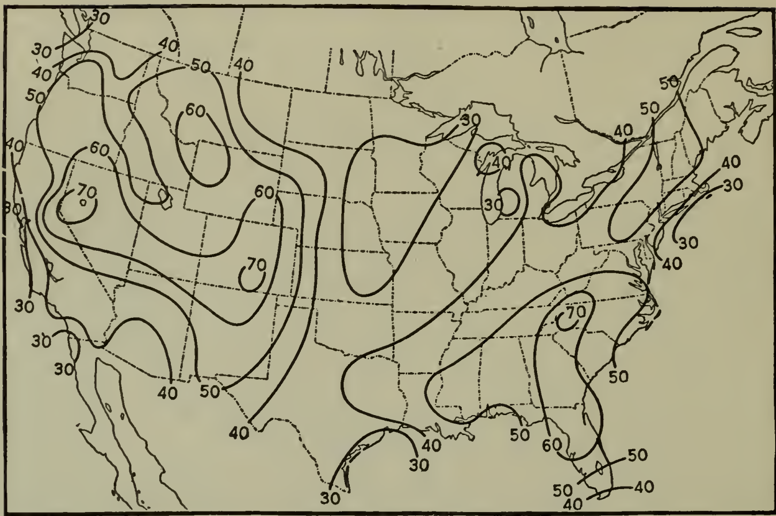

Figure 52. Average Percentage Frequency of Thunderstorms from Noon to 6 P.M., in the United States

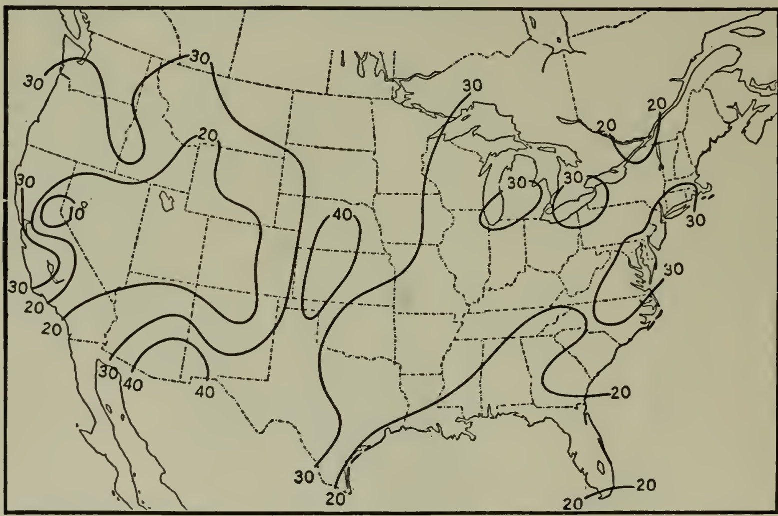

Figure 53. Average Percentage Frequency of Thunderstorms from 6 P.M. to Midnight, in the United States

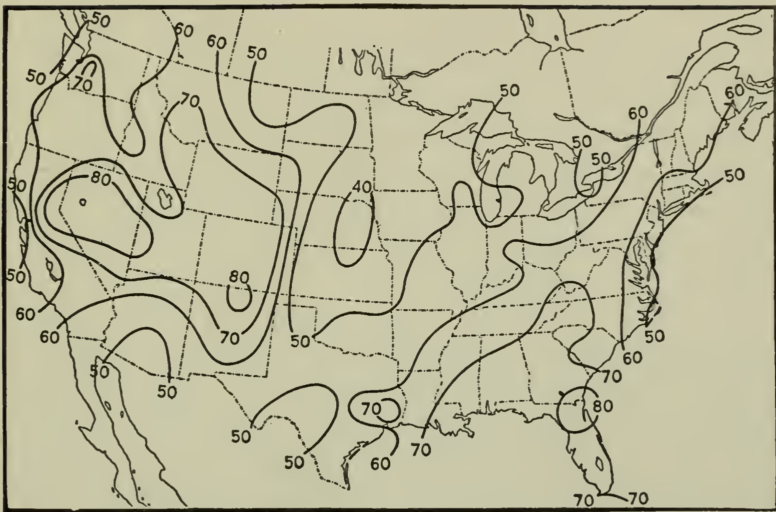

Figure 54. Average Percentage Frequency of Thunderstorms from 6 A.M. to 6 P.M., in the United States

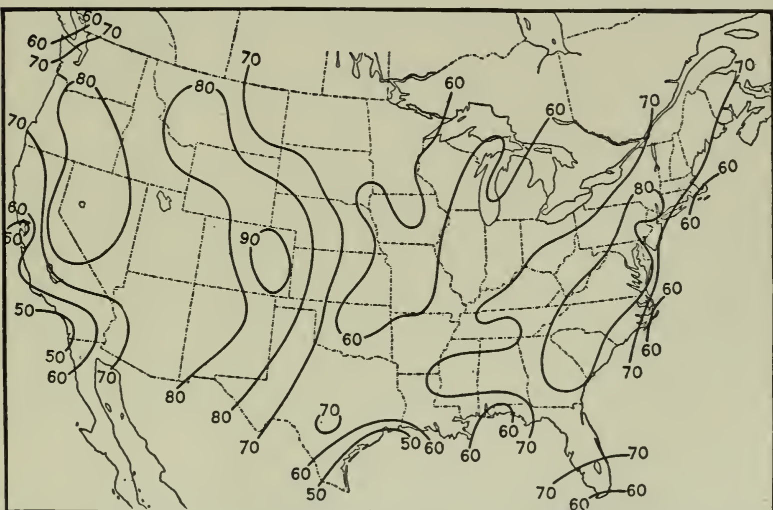

Figure 55. Average Percentage Frequency of Thunderstorms from Noon to Midnight, in the United States

In parts of Wisconsin, Minnesota, the Dakotas, Nebraska, Iowa, Missouri, and Kansas, less than 30% of the storms occur between noon and 6 P.M. Turning now to Figures 53, 50, and 54, we find that in this area, with extensions to the north-northeast and south-southwest, that is, Minnesota to Texas, more thunderstorms occur at night than during the day; 30% to 40% from 6 P.M. to midnight, and 20% to 25% from midnight to 6 A.M.; more than 60% during the night in eastern Nebraska.

As would be expected, this distribution bears a marked relationship to the occurrence of precipitation. During the summer half of the year, April to September, inclusive, approximately 65% of the rainfall occurs in Nebraska between 7 P.M. and 7 A.M., local time, and more than 55% in a considerable area closely similar to that in which the thunderstorm frequency at night is also more than 55%.[7]

The 12-hourly period with the largest percentage of thunderstorms is that from noon to midnight, Figure 55. In the Rocky Mountain and Plateau regions and along the Atlantic seaboard, excepting a narrow strip on the coast itself, approximately 80% of all thunderstorms occur during this period, principally in the first half of it, noon to 6 P.M., as shown in Figure 52.

An interesting feature of Figure 54 is the 50% line along the Atlantic and Pacific coasts. It is well known that thunderstorms over the oceans occur more frequently at night than during the day, owing to the steeper temperature gradient from the surface upward at night. There is some evidence of this influence in the Lake Region, but very little along the Gulf coast, although the frequency of night thunderstorms decreases by 10% from northern to southern Florida,

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[7] Several writers have presented local studies of the distribution of precipitation in this region, but the most complete and comprehensive discussion is that by J. B. Kincer on "Daytime and Nighttime Precipitation and their Economic Significance," *Monthly Weather Review*, Vol. 44, pp. 628-633, November, 1916. See also W. J. Humphreys, "Differences Between Daytime and Nighttime Precipitation in the United States," *Monthly Weather Review*, Vol. 49, pp. 350-351, June, 1921. And R. DeC. Ward, "The Climates of the United States," pp. 227-228.

and very likely decreases still further over the West Indian and Caribbean waters.

A more detailed study, particularly of the diurnal variation in different seasons, would be of interest. However, a general inspection of the available data indicates that there is little, if any, systematic variation in the winter months. On the other hand, few thunderstorms occur in those months and therefore the main features in Figures 50 to 55 would remain essentially unchanged, if only the summer half of the year were included.

Relation between flying and the diurnal distribution of thunderstorms. In the paper by Kincer[8] previously quoted, there is included a discussion of the economic significance, particularly to agriculture, of the diurnal distribution of rainfall. Attention is called to the fortunate circumstance that, in the comparatively dry states of the Middle West, much of the rain that does occur comes at night when "the moisture penetrates the soil to a much greater depth, little evaporation occurs, usually crusts are not formed, and a maximum of benefit results."

Just the opposite relationship holds, however, in the case of aeronautics. The experienced pilot no longer fears the ordinary local thunderstorm, so long as he can see it. But at night, in spite of the lightning, he cannot make out its size or intensity, cannot be certain just what course to take in order to avoid getting into it. Therefore, the thunderstorm offers a greater hazard to flying in the central states than in the southern, where most of the storms occur in daytime, notwithstanding that the total number in the southern states is nearly double that in the central.

Height. As stated in Chapter 6, on clouds, cumulo-nimbus have a greater vertical thickness than have any of the other types, the average being in the neighborhood of one to two miles

[8] *Loc. cit.*

(1½ to 3 km.). The height of their bases above the surface is usually somewhere between 3,000 and 5,000 feet (900 and 1.500 m.). Their tops range from 2 to 8 or 9 miles (3 to 13 or 14 km.) above the surface. The greater heights seldom occur except in the tropics, although cumulo-nimbus extending to 7½ miles (12 km.) have been observed in Texas.

Duration. On the average, thunderstorms continue for some 6 or 7 hours, but cases have been known in which they continued more than 12 hours. However, owing to the progressive movement of most storms, the duration at any one place is usually less than 2 hours.

Direction and rate of movement. In temperate latitudes most thunderstorms of the cyclonic type move in a general eastward direction in conformity with the upper currents which are from the west in regions of most frequent occurrence of these storms, viz., in the southern part of cyclones. The average rate of movement is 30 to 40 miles per hour (50 to 65 km.) in the United States and 20 to 30 miles (30 to 50 km.) in Europe. Storms of the heat or local type common in the southern states, which often occur when pressure distribution is ill-defined, move more irregularly as to both direction and speed. Many of the storms in Texas, for example, travel from east to west and in the tropics they do so as a rule. Thunderstorms in mountainous regions occasionally remain practically stationary until they have "rained themselves out."

It is important to note that, in the case of thunderstorms in a squall line, the direction of travel of the individual storms does not coincide with that of the squall line itself. The latter, extending southwestward from the low-pressure center and carrying with it the line of storms, moves in a general southeastward direction. Each individual storm, however, has a movement of its own toward the northeast or east-northeast, the direction of travel being determined by the winds at the levels of the main portion of the storm cloud.

Area covered. From a very small beginning, thunderstorms increase considerably in area, the greatest increase occurring along the front, the ratio of length to width being somewhere near 4 or 5 to 1, and the actual dimensions 150 to 200 miles (240 to 320 km.) in length and 40 to 50 miles (65 to 80 km.) in width. In individual cases a still larger area has been noted. Many storms of the heat or local type, of slow movement, spread out in all directions instead of merely at the front.

Thunderstorms and flying. Thunderstorms present three principal sources of danger to the air pilot: (1) the squall or gust wind at the front of the storm; (2) the violent vertical movements within the storm; and (3) lightning. Others of lesser importance are hail, heavy rain, and poor visibility.

1. The squall or gust wind is particularly dangerous in landing and low flying, both of which should be avoided, if possible, near the front of a storm. The chief danger is in the region between the warm ascending current and the cool descending current, *A* and *D* in Figure 48. If one is flying at a low elevation toward the storm, there is at first a tendency to rise, and decided "nosing down" is required to counteract this. Suddenly the ascending current is left and the descending current entered; there much skill, aided by luck, is necessary to prevent a crash.

Cases have been reported in which pilots have turned back rather than enter a storm, which was a very wise and proper thing to do, but then encountered great difficulty in landing because at the ground and just above it they ran into the descending current and therefore into a strong tail wind. In one of these cases, the pilot was obliged to take the air again and fly several miles ahead of the storm before a landing could be made in safety.

Another flyer, while stunting in front of a thunderstorm, was astonished to find, after completing three loops, that he

had gained 3,500 feet (1,100 m.) in altitude instead of losing the normal 1,500 feet (450 m.).

2. The vertical movements within a thunderstorm (in the region above *D* and *S* in Figure 48) are such that no aircraft should ever undertake to fly through such a storm. All pilots who have done so and lived to tell the tale are agreed that the turbulence is awful to experience. Control of the craft is impossible. Ascending currents of 80 to 100 miles per hour (35 to 45 m.p.s.) have been experienced, as estimated from the change in altitude[9] within a few seconds. In one case a pilot, in desperation, turned his plane straight down with full power on, which meant a speed of 100 miles per hour (45 m.p.s.) plus gravity; nevertheless his altimeter showed that he was going up.

The following account[10] of a balloon in a thunderstorm, translated from Wegener's "Thermodynamik der Atmosphäre," gives an excellent idea of what may be encountered in a well-developed thunderstorm:

We ascended from the exercise ground of the Luftschifferbataillons on a dull sultry summer afternoon. Soon the wind died away completely and the air became oppressively close. After about an hour, during which the cloud layer slowly descended, we found ourselves over a marshy clearing in the forest and we decided once more to throw out ballast in order to reach drier ground. After pouring out about half a bag of sand we slowly rose from the drag rope and began to prepare our frugal evening meal in peace and quiet. Suddenly the air became remarkably cold. A glance at the barometer showed that we had rapidly risen over 6,000 feet (1,800 m.). We were soon in a dense, formless, grey mist, out of which came irregular gusts of wind shortly followed by heavy rain and hail. Simultaneously began a moaning and hissing accompanied by heavy rolls of thunder on all sides. We were caught up in a whirl which set the basket swaying first slowly and then violently from side to side like a pendulum. Suddenly we fell 3,000 feet (900 m.) or so, only to be immediately raised again as rapidly as we had fallen. This violent up and down motion

[9] Paul A. Miller, "Note on Pilot's Observations of Air Currents in and Near Thunderstorms," *Monthly Weather Review*, Vol. 56, p. 315, August, 1928.
[10] G. C. Simpson, "Thunderstorms and Aviation," *The Journal of the Royal Aeronautical Society*, Vol. XXIX, No. 169, pp. 34-35. January, 1925.

was repeated over and over again for half an hour during which period great hailstones poured over us from all sides, so that a layer of water and hailstones nearly a foot deep covered the bottom of the basket. (There seems no doubt that during this period they were caught in the whirl which forms between the warm rising current and the cold descending current.) It is quite impossible to describe the violent swinging and swaying of the balloon in the stormy whirling air currents. The swaying was so extreme that occasionally we were at the same level as the balloon, the cordage which bound the basket to the balloon being at one moment so tightly stretched that it cracked under the tension and the next moment so loose that the ropes hung slack about us.

Finally the loss of gas caused by the turbulent motion was so great that the ascending current, in which we had been held up like a glass ball on a fountain, could no longer support us and we began to fall at a terrific rate. For three minutes we fell from a height of 7,000 feet (2,100 m.) at a rate of about 40 feet a second (27 m.p.h. or 12 m.p.s.) and it was only because the balloon fell into a wood that we were saved from a fatal accident.

3. Lightning is much less of a hazard than are the two that we have been discussing. Nevertheless it constitutes a real danger. For one thing only a small fraction (estimated at 1%) of lightning discharges go to the earth; hence, the probability of aircraft being struck while flying through a storm is very much greater than that of an object on the earth's surface. Again all types of aircraft exercise a small (very small, to be sure, yet a real) attraction, partly because of the metal in them and partly because of the exhaust,[11] which is more highly ionized than is the surrounding air.

Finally, and as the best proof of the hazard that lightning offers, many authentic cases are on record of aircraft having been struck. In some of these cases the craft were destroyed and the occupants killed. Three free balloons and all but one of their six occupants suffered this fate in the Gordon Bennett Race of 1923. A tragic event for meteorology was the loss of Dr. C. LeRoy Meisinger who with Lieut.

[11] W. J. Humphreys, "Aircraft and the Thunderstorm," *Aviation*, November 16. 1929, p. 981.

James T. Neely was killed in 1924 when their balloon was either struck by lightning or destroyed by an explosion from a static discharge.[12]

Zeppelin airships have been struck several times by lightning, with local fusing of the girders, but as a rule with little other damage. This fusing of some of the metal parts prompts the suggestion that gasoline tanks should always be inclosed in metal to avoid the risk of having holes burned into them.

There are about half a dozen authentic cases of airplanes having been struck by lightning, some of these resulting in the destruction of the planes and the death of the occupants. Several other disasters may be reasonably attributed to the same cause. Although an airplane may have little effect on the electrical field through which it passes, it may get in the path of a discharge at the instant of that discharge and, as earlier stated, lightning flashes at the cloud layer are of much greater frequency than are those from cloud to earth.

Precautions. The one and only precaution to be observed, if at all possible, is to keep out of thunderstorms. Fortunately there is usually a warning, of at least 20 or 30 minutes, of their approach. Three courses are then open: (1) landing at once, if necessary, by first flying away from the storm until a suitable landing place is found; (2) flying above the storm; and (3) flying around the storm.

In free-ballooning it is accepted practice, when a thunderstorm is approaching, to land at once and get all occupants clear of the car. If possible, the balloon is tied to a tree or otherwise secured; if not, it is deflated. In the event that a landing is impracticable—at sea or over a large lake, for example—an attempt should be made to get above the storm; failing this, go as high as possible, thus at any rate escaping

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[12] For an account of this occurrence and an analysis of the data obtained by Dr. Meisinger in his free-balloon flights the reader is referred to "An Account and Analysis of the Meisinger Free-Balloon Flights," by V. E. Jakl, *Monthly Weather Review*, Vol. 53, pp. 99-107, March, 1925.

from the gust wind near the surface and some of the more violent convection in the lower part of the storm cloud.

Aircraft other than free balloons possess greater freedom of action, being able to follow any desired course, in a horizontal as well as a vertical sense. It is therefore not imperative, or even desirable in many cases for them to land. Nor is it necessary, as a rule, for them to turn back. With practically all thunderstorms of the heat or local type it is a simple matter to go around them, although caution is necessary in doing this at night, lest the pilot depart too far from his airway and lose the lights or get out of range of the radio beacon. In the case of thunderstorms along a squall line, great caution must be observed and, if possible, a course chosen at a high altitude between two storms far apart and at right angles to the line connecting them. Only the faster aircraft, that is, the airplane, should attempt this, and that should turn back at the first indication that there is in reality a *solid* line of thunderstorms. Airships, unless made faster and far more resistant to violent stresses than any thus far constructed, should under no circumstances attempt to cross a squall line.

Flying over the top of a thunderstorm is possible in the case of some of the smaller ones of the local or heat type. This procedure is risky, however, and should not be attempted, except in emergencies or unless the small size and low altitude of the storm make it practically certain that flight can be made above the level where turbulent conditions prevail.

That flying around thunderstorms of the local or heat type, and in some cases flying above the smaller ones, is entirely practicable is evident from the fact that there are very few failures in the Air Mail schedules during the summer season, although this is the time of year in which these storms are most numerous. In the two years 1921 and 1922, every scheduled flight was made in June to August along the Cleveland-Chicago Airway; and all but three between Cleveland

and New York. There were delays, owing to necessary detours, but the essential feature—the completion of the flight—shows that thunderstorms, if their danger and mechanism are properly understood and appreciated, can be eliminated as a factor of serious proportions in the development of commercial aeronautics and the maintenance of schedules.

Tornadoes. These ultra-destructive local storms are the result of vigorous convection between strong, closely bordering countercurrents. They are closely associated with thunderstorms in the right rear quadrant of V-shaped cyclones, though fortunately they are much less frequent. They occur principally in the central Mississippi and Ohio valleys, in some portions of the upper Mississippi valley and in the interior parts of the southern states. They are most numerous in spring and early summer.

The coming of a tornado is usually heralded by clouds in a wild turmoil, varying from inky black, occasionally with greenish or purple hues, to steam-like grays and whites. The different cloud masses at times meet and break up into smaller portions which dart in all directions, some up, some down and all seemingly at odds one with another, until presently there is seen the funnel-like form of the tornado itself. (See Plate XLII.)

Though of great violence, both from the high wind velocities, estimated at 100 to 500 miles per hour (45 to 225 m.p.s.) and the low pressure at their centers—the latter having an explosive effect upon buildings—they are fortunately of small area, 300 to 1,500 feet (100 to 500 m.) in diameter. They almost invariably travel northeastward, with the general upper wind current. There is quite conclusive evidence that one or more occurred in connection with the West Indian hurricane of September, 1929. They were in the right rear quadrant of the hurricane and moved toward the northwest, parallel to the course of the main storm.

Plate XLII. Tornado at Solomon, Kan.

Margaret R. Corts

Plate XLIII. Waterspout over Lake Erie

The paths of tornadoes average about 25 miles (40 km.) in length, but range from 500 feet (150 m.) to 300 miles (500 km.) or more.

No definite information is available as to the height of tornadoes, but it seems likely that this must be very great in some cases; not necessarily the funnel cloud as such, but the extreme turbulence along the wind shift line which gives rise to the tornado.

What to do. A free balloon should land immediately. The pilot of an airplane or an airship, however, as a rule would have time to get away and should attempt to do so, by flying toward the northwest, if the tornado is coming directly toward him. In the event that a tornado appears suddenly in the vicinity of the flyer, quick decision must be made as to the greater likelihood of escape in landing or in flight.

Waterspouts. Many waterspouts are simply tornadoes over water. (Tornadoes were formerly called landspouts.) Other waterspouts, of small size and intensity, are the sea counterpart of dustwhirls. Waterspouts are comparatively infrequent, but may occur wherever there is a boundary of sharp temperature contrasts, as for example, the northern border of the Gulf Stream and off the east coast of the United States. Plate XLIII shows a waterspout over Lake Erie.

References for chapter: In addition to the works listed in Appendix 5, under "General Treatises" and "Thunderstorms" and to those referred to in the text, the following have been found most helpful in the preparation of this chapter.

G. C. Simpson, "Thunderstorms," *Quarterly Journal of the Royal Meteorological Society*, Vol. 53, No. 222, pp. 172-176, April, 1927. G. C. Simpson, "Lightning," *Nature* (Supplement), Vol. 124, pp. 801-812, November 23, 1929. G. C. Simpson, "The Mechanism of a Thunderstorm," *Proceedings of the Royal Society of London*, Vol. CXIV, No. 768, pp. 376-401, April, 1927. C. L. Meisinger, "The Thunderstorm and the Aviator," *U. S. Air Services*, pp. 11-15, January, 1924. C. F. Brooks, "The Local or Heat Thunderstorm," *Monthly Weather Review*, Vol. 50, No. 6, pp. 281-284, June, 1922. W. H. Alexander, C. F. Brooks, and G. H. Burnham, 'Thunderstorms in Ohio during 1917," *Monthly Weather Review*, Vol. 52, No. 7, pp. 343-348.

CHAPTER 9

CYCLONES AND ANTICYCLONES

The most conspicuous features of a weather map are the systems of low and high barometric pressure, called respectively "cyclones" or "lows" and "anticyclones" or "highs." There are two general classes of each of these two types of pressure distribution: (1) the large, more or less stationary and semi-permanent areas caused by distinct temperature differences in adjacent regions, for example, the so-called "Bermuda High," the "North Pacific High," the "Aleutian Low," etc.; and (2) the more familiar areas that follow one after the other in more or less regular order and that bring to a region over which they pass the successive changes in weather characteristic of temperate latitudes. Examples of the latter class are shown in Figure 56.[1] Although closely associated one with the other, cyclones and anticyclones are widely different in most respects and will therefore be treated separately. One feature common to both, however, is the relation of the wind direction to the pressure gradient, first expressed by Buys-Ballot.

Buys-Ballot's law. "If you stand with your back to the wind, the region of low pressure will be on the left hand in the Northern Hemisphere and on the right hand in the Southern Hemisphere."

That the wind does not blow directly from high to low pressure is owing to the deflective effect of the earth's rotation; that the winds at the surface are not strictly parallel to the isobars is because of friction and viscosity. These influences have been discussed in Chapters 1 and 4.

[1] From "Weather Forecasting," by George S. Bliss, Bulletin No. 42, W. B. 972, 1929.

In a general way, also, the relation of wind velocity to pressure gradient is of the same order in both pressure systems, that is, velocity increases as the gradient becomes stronger. However, it is important to recognize that, for the same gradient, latitude, and curvature of the isobars, winds are somewhat stronger in anticyclones than in cyclones.

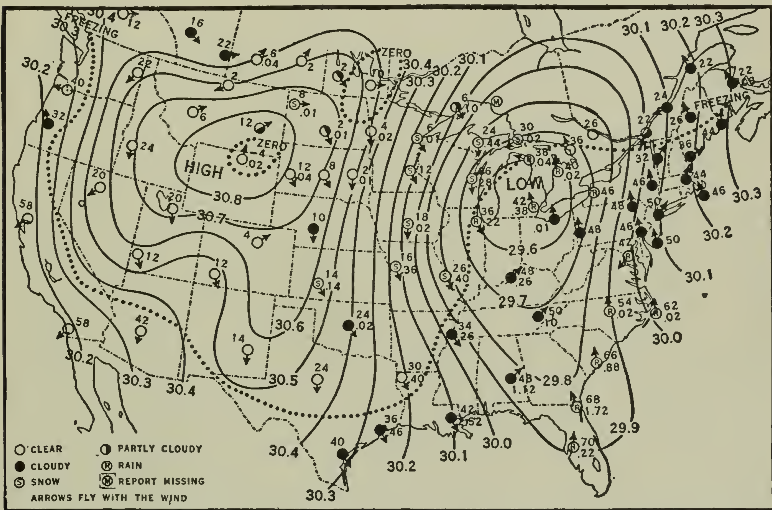

Figure 56. Daily Weather Map, November 28, 1911, Based on Observations at 8 A.M., 75th Meridian Time (after Bliss)

Isobars, solid lines, pass through points of equal air pressure (in inches; 1 inch = 25.4 mm. = 33.9 mb.). Isotherms, dotted lines, pass through points of equal temperature and are drawn for freezing and zero only (32° and 0° F.; °0 and −18° C.). First figures indicate lowest temperature, ° F. (° F. = 9/5° C. + 32), during last 12 hours; second, 24-hour precipitation when 0.1 in. (0.25 mm.) or more; third, wind velocity when 10 or more miles per hour (4.5 m.p.s.).

Almost invariably the strongest winds are found in the latter but this is entirely because the gradients there are much steeper than in anticyclones.

Cyclones

General characteristics. As indicated in Figure 56, a cyclone is a system of winds that accompanies or surrounds any considerable region of minimum pressure. The winds are directed spirally inward, counterclockwise, toward the cen-

ter of lowest pressure at an angle of 20° to 40° across the isobars. Cyclones are usually accompanied by generally cloudy weather and precipitation; and much higher temperatures in the eastern than in the western half, in conformity with the fact that the winds in the eastern half have in most cases large southerly components, while those of the western half have large northerly components. There are in individual cases innumerable variations in all these features. Lows that increase greatly in intensity have isobars that are approximately circular. This, however, is the less usual type as by far the greater number of depressions have a trough form.

This general class may include the "V" shape, the inverted V, and the elliptical form. In the V type, the central isobars, of which there may be several, are more or less circular, but the isobars next outward from them have the form of a V, the open end of the V to the north. In such cases, Highs are generally located to the west and to the southeast of the Low's center. In the inverted V type, the isobars may be similarly described, except that the pressure system is inverted in a north and south sense, the opening of the V being to the south. The Highs in such cases are located to the northeast and northwest of the low center. In the elliptical type the isobars are oval, the major axis being to the minor axis in the ratio of 2 or more to 1. There may be a center in one end of the oval or there may be a center in each end and occasionally a third center in the middle. The outer isobars on the east and west sides frequently trend north and south and may be approximately straight. A system with several centers does not retain its form for any great length of time because one of the centers deepens and the whole system changes shape, most frequently into the V type. V-shaped Lows are generally characterized by showers, as distinguished from steady rain. In well-marked cases, squalls occur along the wind-shift line, as winds change from a southerly to a northerly quarter.

Secondaries are developments of separate centers within the general area of a major disturbance. In the United States, these secondaries often occur in the southeast quadrant of the parent disturbance and at other times, along and in the southern end of its trough. This trough may assume different orientations, as for example: northeast-southwest, northwest-southeast, and sometimes east-west. In the inverted V type of Low, secondaries occur in the northern end of the trough. The rule may be generally stated that they occur in the narrow end of the trough. Secondaries travel in the same general direction as the parent disturbance. In summer the map frequently shows several nearly stationary, shallow Lows, a type accompanied by little wind but numerous showers and thunderstorms. On the average, the heaviest precipitation occurs in the southeast quadrant of cyclones moving from a general west to east direction. In the central portions of the United States, however, the largest percentage is found to the north and northwest of the center.[2]

An important exception to the usual temperature distribution occurs in winter cyclones that enter the United States from the Pacific Ocean. Here, because of the characteristic difference between marine and continental temperatures, the southerly winds on the east side of the cyclone are colder than the northerly winds on the west side. With eastward movement, however, the normal distribution is gradually established.

Size. Cyclones vary in size, or extreme limits of influence, from 300 or 400 to 2,000 miles (500 or 650 to 3,200 km.) in diameter, with an average in the United States somewhere between 1,000 and 1,500 miles (1,600 to 2,400 km.). They are frequently still larger in the North Atlantic and North Pacific.

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[2] Vincent E. Jakl, "A Preliminary Study of Precipitation in Relation to Winds and Temperature," *Monthly Weather Review*, Vol. 52, pp. 18-22, January, 1924. Anton D. Udden, "A Statistical Study of Surface and Upper Air Conditions in Cyclones and Anticyclones Passing over Davenport, Iowa." *Monthly Weather Review*, Vol. 51, pp. 55-68, February, 1923.

Types in the United States. In North America, cyclones are classified according to the regions in which they first enter or appear, as follows: Alberta, North Pacific, South Pacific, Northern Rocky Mountain, Colorado, Texas, East Gulf, South Atlantic, and Central.

Frequency. The Alberta type is by far the most frequent, constituting nearly two-fifths of the total number. The East Gulf and South Atlantic types are the least frequent. The average number, monthly and annual, for all types combined, is as follows:[3]

Jan.	Feb.	Mar.	Apr.	May	June
13	11	12	10	10	8

July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
9	8	9	10	12	12	124

These figures show that the ratio of winter to summer frequency is about 10 to 7.

Direction and rate of movement. Storms of all types, except those of tropical origin in their earlier stages, travel in a general eastward direction, nearly all in this country passing out across or near the New England states. On the average those originating or first appearing in western Canada first move southeastward, then northeastward; those in the central and western states, eastward, then northeastward; and those in the southern and southeastern states, northeastward. The average annual rate of movement varies from 548 miles (882 km.) per day for the northern Rocky Mountain type to 656 miles (1,056 km.) for the Texas type. In individual cases it ranges from practically zero to well over 1,000 miles (1,600 km.). The average monthly and annual 24-hour movement for all types combined is as follows:[4]

	Jan.	Feb.	Mar.	Apr.	May	June
Miles...........	745	690	673	542	492	480
Kilometers......	1,199	1,110	1,083	872	792	772

[3] From E. H. Bowie, and R. H. Weightman, "Types of Storms in the United States and their Average Movements," *Monthly Weather Review*, Supplement No. 1, W. B. No. 538, 1914.
[4] *Ibid.*

	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
Miles..............	521	489	549	571	646	718	602
Kilometers..........	838	787	884	919	1,040	1,156	969

Results of numerous studies have shown that the direction and rate of movement of cyclones are approximately those of the upper winds. In the United States, the height at which this relation is closest, on the average, appears to be about 3

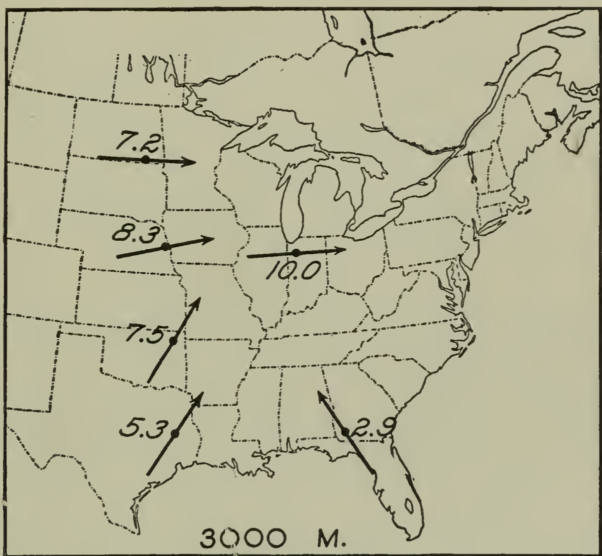

Figure 57. Summer Resultant Winds, m.p.s., in Eastern and Central United States at 3 kilometers (10,000 ft.) Above Sea Level
To convert m.p.s. to m.p.h., multiply by 2.2.

kilometers (10,000 ft.), as shown by Figures 57 and 58, which give the resultant winds at that height for summer and winter, respectively.[5] The average movement of cyclones for summer and winter (see foregoing table) is 9.3 and 13.4 meters per second (21 and 30 m.p.h.), respectively; these values agree closely with those presented in Figures 57 and 58.

[5] *Resultant* winds are determined by resolving the observed directions and velocities into their N and W (or S and E) components and adding these algebraically. In computing *average* winds the directions and velocities are considered separately.

Tropical cyclones. Tropical cyclones differ in many respects from the cyclones of temperate latitudes. They are of smaller diameter, 50 to 1,000 miles (80 to 1,600 km.); they are more nearly circular; the pressure gradient is as a rule much steeper, the winds therefore much stronger and the pressure at the center much lower; the "eye" of the storm is well developed, the sky there being visible and the wind

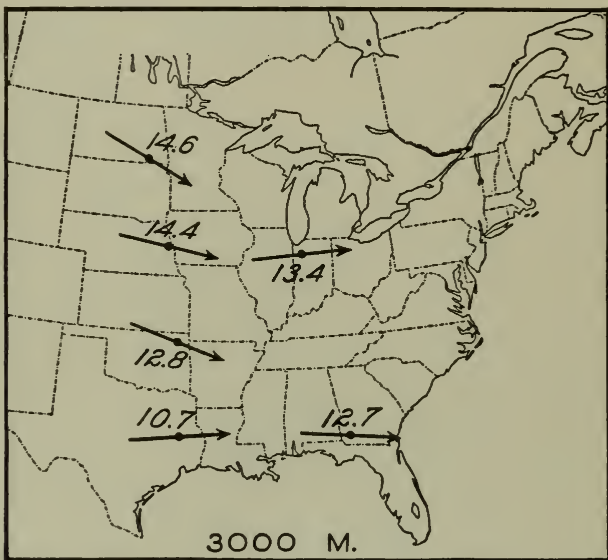

Figure 58. Winter Resultant Winds, m.p.s., in Eastern and Central United States at 3 kilometers (10,000 ft.) Above Sea Level
To convert m.p.s. to m.p.h., multiply by 2.2.

relatively light; and they occur in the hottest part of the year. In the north Atlantic they are called *hurricanes;* in the western Pacific, *typhoons;* near the Philippines, *baguios;* and in the Indian Ocean, simply *cyclones.* Hurricanes occur almost altogether in the summer half of the year, from June to November, inclusive. The months of greatest frequency are September and October, but many severe storms occur also in August. Since 1878 there has been at least one each year,

and the maximum number was 16; the average for this period was 6. Fortunately, however, the number of severe storms that affect the United States is only about one in 2 or 3 years. Those in the early and late months originate, as a rule, in the western Caribbean Sea; those in the mid-season more frequently near the Cape Verde Islands. The former move northward or northwestward into the Gulf of Mexico, then northeastward, entering the United States along the Gulf coast, or north and northeastward over Cuba; the latter move westward, then northward and finally northeastward. In many cases these do not reach the United States but recurve to the east of the Bahamas. Fortunately, the storms that enter this country soon increase in area and decrease in intensity, assuming the characteristics of the ordinary cyclones.[6]

Anticyclones

General characteristics. As indicated in Figure 56, an anticyclone is a system of winds that accompanies or surrounds any considerable region of maximum pressure. These winds are directed spirally outward, clockwise, from the center of highest pressure at a much larger angle to the isobars than in the Low, often nearly 90° near the center. Anticyclones are attended by generally clear weather; and lower temperature in the eastern than in the western half. Owing to the clear weather, the loss of heat by radiation is greater than the amount received from insolation, with the result that anticyclones are cooler in summer than cyclones and much colder, with "cold waves" at times, in winter. Although clear weather is the rule, light rain occasionally occurs in the southern and western quadrants and light snow in the eastern half. Occasionally, also, fog forms in winter and light precipitation with thunderstorms in summer in the saddle, or "col," between two

[6] For detailed information regarding tropical cyclones, the reader is referred to "West Indian Hurricanes and Other Tropical Cyclones of the North Atlantic Ocean," by C. L. Mitchell, *Monthly Weather Review*, Supplement No. 24. 1924.

anticyclones, owing to mixing of the air circulating around the two centers.

Size. Well-defined anticyclones are never as small as the smallest cyclones, and many of them cover a larger area than the largest cyclones; in some cases they have dominated conditions in practically all parts of the United States. In general, however, they vary roughly between 700 or 800 and 2,500 miles (1,100 or 1,300 to 4,000 km.) in diameter.

Types in the United States. The same basis of classification is used as with cyclones, viz., the region of entry or development. The types are: North Pacific, South Pacific, Alberta, Plateau and Rocky Mountain Region, and Hudson Bay.

Frequency. Again, the Alberta type is by far the most frequent, constituting 50% of the total number. The Hudson Bay and South Pacific types are least frequent. The average number, monthly and annual, for all types combined, is as follows:[7]

Jan.	Feb.	Mar.	Apr.	May	June
9	8	8	8	7	5

July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
7	7	8	8	8	9	92

The ratio of summer to winter frequency is about 2 to 3; and of all anticyclones to all cyclones, about 3 to 4.

Direction and rate of movement. Anticyclones move in a general eastward direction, but somewhat farther south as a rule than cyclones. The Hudson Bay type usually follows a southeastward course. The majority of all types leave the United States along the middle Atlantic coast. The average annual rate of movement is about 450 miles (720 km.) per day for the Hudson Bay type and about 550 miles (880 km.)

[7] From E. H. Bowie and R. H. Weightman, "Types of Anticyclones of the United States and their Average Movements," *Monthly Weather Review*, Supplement No. 4, W. B. No. 600, 1917.

for the other four types. The range is about the same as that of cyclones, zero to 1,000 miles (1,600 km.), but a larger proportion move slowly, occasionally remaining practically stationary for a week or more. The average monthly and annual 24-hour movement for all types combined is as follows:[8]

	Jan.	Feb.	Mar.	Apr.	May	June
Miles	624	588	585	545	521	484
Kilometers	1,004	946	941	877	838	779

	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
Miles	483	487	545	548	562	570	544
Kilometers	778	784	877	882	904	917	875

The average summer and winter speeds are 9.0 and 11.1 meters per second (20 and 25 m.p.h.), respectively, somewhat less than those of cyclones. The latter were found to agree closely with the resultant winds at about 3 kilometers (10,000 ft.), Figures 57 and 58. It is evident, then, that anticyclones do not reach as great a height on the average as do cyclones. Mitchell[9] has found that "the rate of movement of the anticyclone is roughly proportional to the speed of the free-air winds at and above the 2,000-meter (6,600 ft.) level."

Upper Air Conditions in Cyclones and Anticyclones

Since winds blow at an angle to the isobars in the lower levels (see Figure 56), it follows that the air has an upward component in cyclones and a downward component in anticyclones. This results in cooling of the air in the former and warming in the latter, which processes are responsible for condensation in the first and evaporation in the second. Other conditions being equal, we should expect to find cyclones colder than anticyclones, but importation of air from warm and cold regions modifies and in most instances overcomes the thermal effects of vertical movements, which in the anticyclone are

[8] *Ibid.*.

[9] Charles L. Mitchell, "Relation between Rate of Movement of Anticyclones and the Direction and Velocity of Winds Aloft (West and Southwest of Highest Pressure)," *Monthly Weather Review*, Vol. 50, pp. 241-242, May, 1922.

small. Considered as units, cyclones appear on the average to be colder than anticyclones in Europe except near the surface. In the eastern part of the United States they are warmer up to 2 kilometers (6,600 ft.) and about the same temperature between 2 and 5 kilometers (6,600 and 16,000 ft.). In

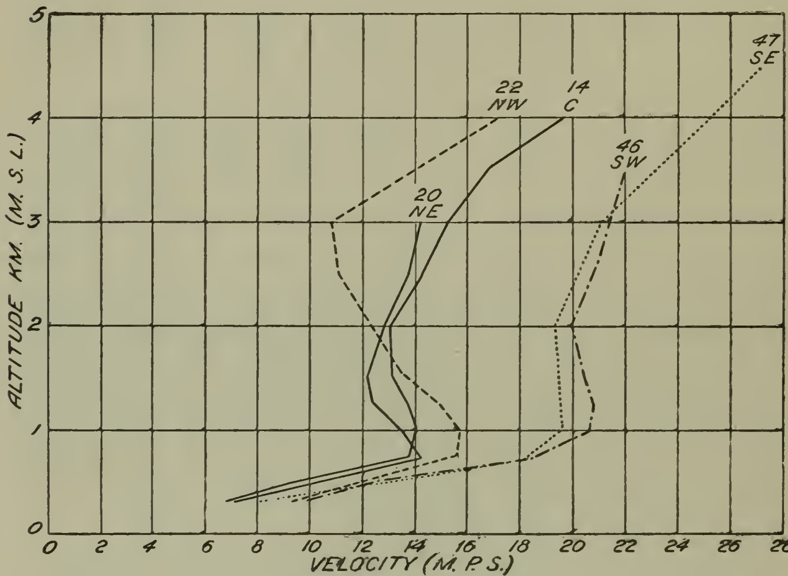

Figure 59. Average Winter Wind Velocities in Different Parts of Cyclones in Northern United States

NE, SE, SW, and NW refer to those quadrants and C to the central part of the cyclones. To convert kilometers to feet, multiply by 3,300; m.p.s. to m.p.h., multiply by 2.2.

the interior, however, cyclones continue warmer from the surface to 5 kilometers (16,000 ft.) although the difference is not large above 3 kilometers (10,000 ft.). These statements refer to the air vertically above the surface positions of the cyclonic and anticyclonic centers. In reality, owing to the effects of temperature on air density, the lowest and highest pressures in the upper air are considerably shifted from their surface positions, northwestward in cyclones and southwestward in anticyclones, the amount of the shift depending on

the steepness of the horizontal temperature gradient. In the upper levels, moreover, owing to the straightening out of the isotherms, the isobars gradually open out into broad sweeping curves. These changes occur at comparatively low altitudes, 1 to 3 kilometers (3,300 to 10,000 ft.), if the temperature

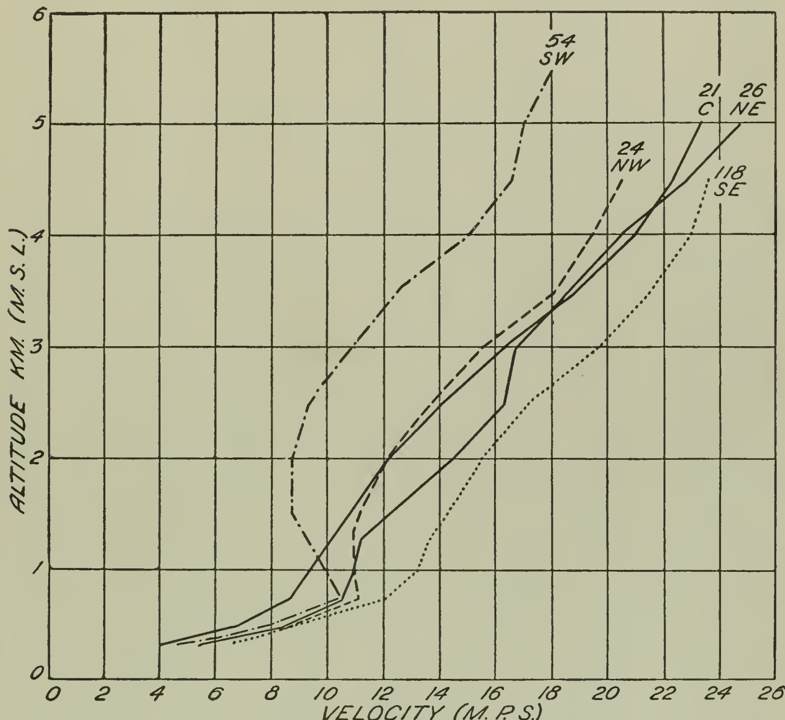

Figure 60. Average Winter Wind Velocities in Different Parts of Anticyclones in Northern United States

NE, SE, SW, and NW refer to those quadrants, and C to the central part of the anticyclones. To convert kilometers to feet, multiply by 3,300; m.p.s. to m.p.h., multiply by 2.2.

contrast is large; therefore, cyclones and anticyclones are seldom symmetrical to any great height in winter. In summer, if temperatures are comparatively uniform over much of the country, cyclones and anticyclones extend as such to great heights; in general, tropical cyclones reach greater altitudes than do those in temperate latitudes for the same reason.

The turning of winds with altitude has been discussed in an earlier chapter and it is only necessary to apply the general principles there given to the surface winds appropriate to dif-

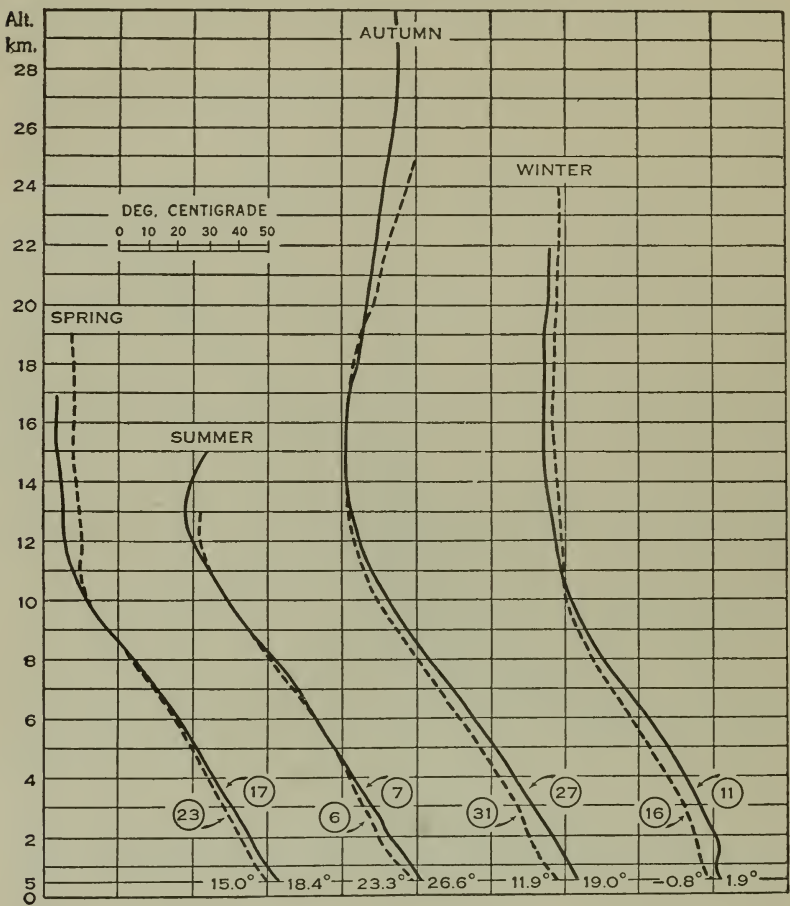

Figure 61. Average Temperatures Over Falling Sea Level Air Pressure (Solid Lines) and Over Rising Sea Level Air Pressure (Broken Lines); or with South and North Component Winds, Respectively

Numbers in circles indicate numbers of observations on which curves are based. To convert kilometers to feet, multiply by 3,300; ° C. to ° F., multiply by 1.8 and add 32.

ferent parts of cyclones and anticyclones. For example, the southeasterly winds east of a cyclone veer to southwesterly in the upper levels because the lowest pressure shifts northwest-

ward with altitude from its surface position. The normal wind distribution in the upper levels is then southwest to west-southwest over the major part of cyclones, and northwest to west-northwest over the major part of anticyclones. The winds above cyclones are strongest in the southern part and weakest in the northern; above anticyclones they are strongest to the east of the center and weakest to the west. These characteristic relationships are well shown in Figures 59 and 60, based on a detailed discussion of the subject by Samuels.[10]

The wind circulation thus set up by temperature distribution in the lower levels, in turn affects the temperature distribution in the upper levels. It has been observed that the south component winds above the surface positions of cyclones cause higher temperatures there than are found above anticyclones, where north component winds prevail. The difference is greatest in the interior of the country during the winter when latitudinal temperature contrasts are large. At all levels in the troposphere it is found, in general, that the region where pressure is rising, that is, where air movement is from a northerly direction, is colder than that in which pressure is falling. It is interesting to note that the reverse relationship holds in the stratosphere, as indicated in Figure 61. In both the troposphere and stratosphere, the chief influence in determining the temperature is the source of the air, or the direction of the wind. Falling pressure is generally accompanied by south component winds. These come from a warm source in the troposphere, but from a *cold* source in the stratosphere, the latter being coldest over the tropics, as stated at the beginning of Chapter 3. With rising pressure and north component winds, the opposite temperature relation is found.

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[10] Leroy T. Samuels, "A Summary of Aerological Observations Made in Well-Pronounced Highs and Lows," *Monthly Weather Review*, Vol. 54, pp. 195-213, May, 1926.

CHAPTER 10

WEATHER FORECASTING

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Introduction. Meteorological observations serve two main purposes: (1) the collection of statistical information of value as such for climatological and statistical purposes, which is also necessary for studying and explaining the physical causes of various atmospheric phenomena, and, as a direct consequence, increasing the accuracy of weather forecasting; (2) the furnishing of current information and forecasts of immediate practical value.

Observations. In this day and age all worthwhile forecasts, except for short periods in advance, are made from charts based on simultaneous observations. In the United States, the Weather Bureau maintains about 200 stations manned by trained observers and equipped with standard observing and recording instruments. Observations are made twice daily at 8 A.M. and 8 P.M., 75th meridian time. These observations furnish the basis for all the forecasts, whether for agricultural, commercial, navigational, or aviation interests. Telegraphic reports of observations are forwarded to collecting centers at Chicago and New York in the morning and at Chicago at night, where effective telegraphic facilities are available. Prior to the receipt of the reports at the reception centers, addressed blanks are prepared, one for each station designated to receive the reports coming to the center. For example, the report from New Orleans may go to 100 different points, in which case 100 separate blanks are pre-

pared, each one having its proper address. When the New Orleans report is received at the center, the message is copied on a stencil and from the stencil the hundred messages are duplicated and rushed to appropriate wires for immediate transmission. Under the present system all reports are transmitted from the observation station to the stations of ultimate destination in a period of between 30 and 45 minutes. These reports, in addition to about 50 from Canada and Alaska, are distributed by telegraph not only to the district forecast centers but to the larger field stations throughout the country. They also are broadcast by radio on several different wave lengths as soon as received at Washington and San Francisco, and are thus made available promptly in all their detail to the nation at large.

Charting the data. At the district forecast centers and the local stations, the data are charted on base maps. Weather maps are published each week-day morning at about 50 stations. Most of them are printed by means of a chalk plate, but a few are issued by stencil process. Such maps show on the face of the map isobars, isotherms, wind direction, and state of the weather; in addition there appears in tabular form, the precipitation, the velocity of the wind, and the maximum and minimum temperatures. The forecasts with a summary of weather and temperature conditions also are given.

Forecast districts. For general forecast purposes the United States is divided into five districts, as shown in Figure 62. The forecasts for these districts are issued at Washington, Chicago, New Orleans, Denver, and San Francisco. At these centers the observational material is first entered on a principal chart and auxiliary maps consisting of pressure change, temperature change, cloud, and upper air are prepared. The forecasts are then made for each state in the district and warnings of frosts, cold waves, and storms are disseminated as occasion demands. In addition, special forecasts for avia-

tion are made by zones and by routes, as will be mentioned later. The state forecasts and warnings are issued twice daily. The morning forecasts cover conditions during the coming night and the following day, while those made at night are for 36 hours, beginning at 8 A.M. the next day, except on the Pacific coast where they are for 24 hours. Every attention has been devoted to making their distribution as complete as possible. Probably the greatest distri-

Figure 62. Forecast Districts in the United States

bution is obtained through the press. The next most important medium is the radio by reason of the availability to remote and otherwise inaccessible places. Rural telephone lines and the mails also are used to a large extent.

Aviation zones. One type of forecasts for aviation is made by zones which are indicated on Figure 63. They are made at the District Forecast Centers at Washington, Chicago, New Orleans, Denver, and San Francisco. The morning issue covers the afternoon hours, while those made at night cover the following day. They are of a general character, similar to the state forecasts but deal with conditions more

particularly as they affect flying, giving the winds at the surface and at about 5,000 feet (1,500 m.).

Aviation routes. Forecasts for special routes are issued twice daily from the District Forecast Centers and are more specific than the zone forecasts. Some of these are made for the same period as the zone forecasts and others cover particular scheduled flights. More of this work, but of a somewhat different character, is done at the principal airport

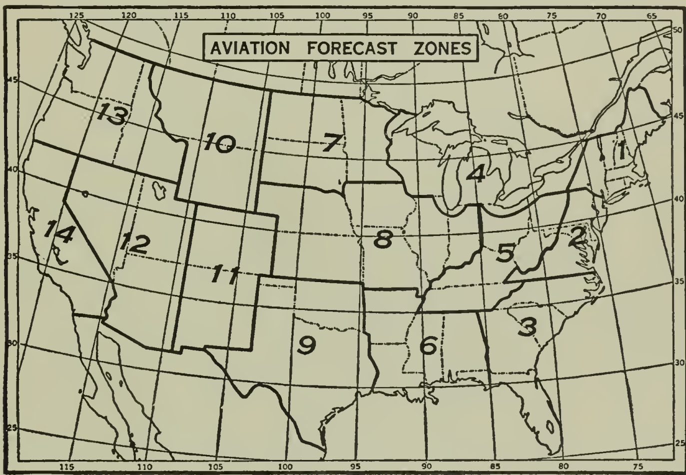

Figure 63. Aviation Forecast Zones in the United States

Forecasts of weather conditions and of wind at surface and aloft are issued twice daily for the benefit of aviators. They are made at approximately 9:30 A.M. and 9:30 P.M. (75th meridian time), and cover a period of 6 to 12 hours, beginning at noon and midnight, respectively. The forecasts for the various zones are prepared and issued from forecast centers of the Weather Bureau, as follows: Washington, D. C.—Zones 1, 2, 3, and 5. Chicago, Ill.—Zones, 4, 7, and 8. New Orleans, La.—Zones 6 and 9. Denver, Colo.—Zones 10 and 11. San Francisco, Cal.—Zones 12, 13, and 14.

stations where shorter period and still more specific forecasts are made for particular routes. These are based on more detailed and more frequent reports than are available at the District Forecast Centers.

The principal airport stations have been established in connection with "Commercial Airways" which are designated and established by the Department of Commerce when flying becomes sufficiently developed to warrant such action. When

a route is designated a "Commercial Airway" the next step is for the Weather Bureau, after request by and collaboration with the Department of Commerce, to supply the meteorological service along the airway. To this end airport stations are established at the terminals, and if the route is of sufficient length, at intermediate points. In addition, intermediate reporting stations furnish frequent weather reports, hourly in some cases and at others less frequently, depending on the amount of flying. Many of these are now and others will later be connected by teletype service over leased wires, which insures efficient and immediate communication along the entire airway. So far as these special forecasts are concerned the regular Weather Bureau observations from its approximately 200 stations form the groundwork. On some of the airways the observations already referred to are supplemented by reports every 3 hours from Weather Bureau and special stations off the airway, but not more than 300 miles on each side of it. Meteorologists at the airport stations have also the benefit of the hourly reports along the airway itself. The current reports of sky and ground conditions, including visibility, fog, etc., are made available at frequent intervals to the stations along the airway for the benefit of the pilots; also the trained meteorologists at the airport stations make short-period forecasts, called "trip forecasts" for pilots just before the beginning of a trip. These short-time forecasts, averaging about 3 hours, together with the existing weather and landing conditions at the fields, are broadcast by convenient radio stations established and maintained by the Department of Commerce. Any pilot, therefore, before leaving his field can obtain the latest information as to conditions along the route, which is checked and supplemented by radio broadcasts that he can pick up while in the air, after the take-off.

Commercial air routes are now established, and intensified service functioning over a large part of the country as shown in Figure 64.

Figure 64. Commercial Airways for Which Intensive Weather Service Is Provided

The system of commercial airways is rapidly expanding. This map gives the picture for 1930. The routes shown will probably continue and others will be added until the country is covered by a complete network.

Making the forecasts. The general forecasts, as well as the special ones, are based to a large extent on the movement of Lows and Highs which are described in the previous chapter under the title "Cyclones and Anticyclones." A number of general rules have been developed as a result of experience, some of which have been published by Major Edward H. Bowie.[1] It may be said in passing that the only way to gain worthwhile results in forecasting is by a careful and intelligent study of the weather maps, postulating, of course, a good grounding in meteorology. In addition, an intimate familiarity with the different types of Highs and Lows and their behavior under different conditions is a requisite, as well as a knowledge of the structure of Highs and Lows, the precipitation processes and their interpretation from information available on the map under consideration. A scheme of forecasting which bears the name of the Bjerknes' System is a most profitable one to pursue if it is desired to keep abreast of more recent developments in the science. However, even the most adept exponents of this system find it necessary to study carefully the weather charts of the past in order to apply the scheme to the best advantage.

The Bjerknes' method. According to the Bjerknes' System,[2] a cyclone consists of two essentially different air masses, as shown in Figure 65: a warm current of south or southwest winds in the region of the cyclone and its trough, with cold air at the rear and also at its front. These air masses are separated by fairly distinct boundary surfaces, which pass through the center of the cyclone. Surfaces of discontinuity are inclined in the vertical always toward the cold side at an angle of slope of the order of 1 to 100 or 1 to 150. The middle portion of the figure shows the plan of

[1] "Types of Storms in the United States and Their Average Movements," *Monthly Weather Review*, Supplement No. 1, and "Types of Anticyclones in the United States and Their Average Movements," *Monthly Weather Review*, Supplement No. 4, by Bowie and Weightman.

[2] J. Bjerknes and H. Solberg, "Life Cycle of Cyclones and the Polar Front Theory of Atmospheric Circulation," *Geofysiske Publikationer*, Vol. 3, No. 1, 1922, Oslo. (Summary in *Monthly Weather Review*, Vol. 50, p. 468, September, 1922.)

the surface air currents about a Low. At the center the warm and cold fronts meet as represented in the figure by broken lines. The upper portion of the figure shows a vertical east-west section through the cyclone north of its center. Here

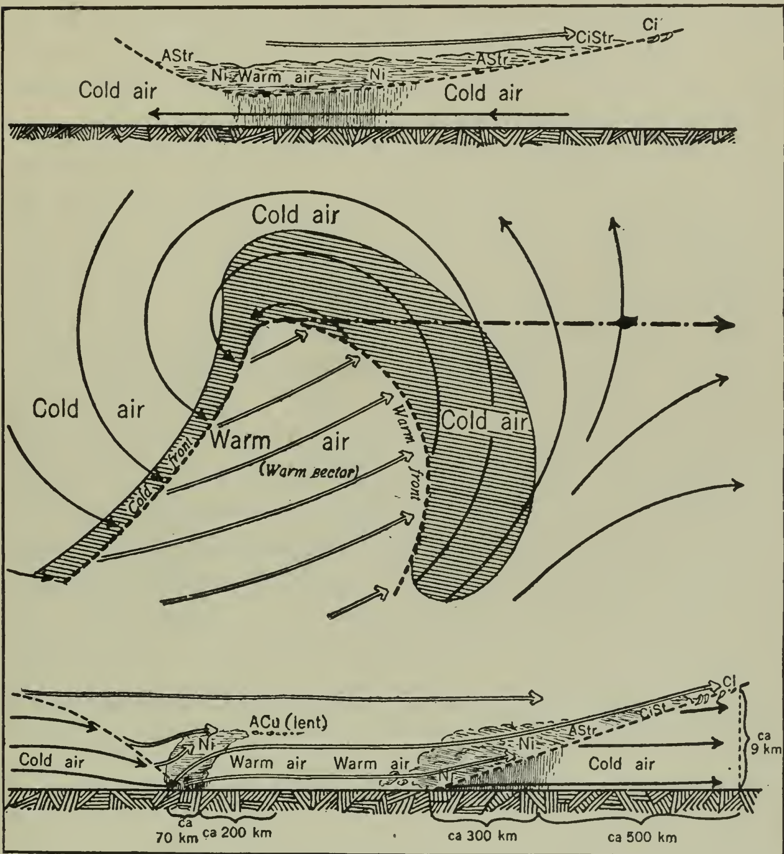

Figure 65. Bjerknes' Ideal Polar-Front System

the air at the surface is moving from an easterly or northerly quarter and is relatively cold, as we find frequently in the northern quadrants of a Low. Aloft the wind is from the south or southwest, and being of tropical origin is relatively

warm and humid. It came originally from lower levels and lower latitudes, having undergone a forced ascent over the cold wedge of surface air with the result that there is considerable cloudiness and precipitation due to cooling through ascent and adiabatic expansion. The lower portion shows another vertical east-west section through the cyclone south of the center. At the left are seen the cold polar surface winds from the west and northwest, underrunning the warm tropical south and southwest winds, which latter persist aloft after the wind has changed to westerly at the surface. This underrunning results in forced ascent of warm, moist air from the south with resulting cloudiness and heavy, and as a rule, brief showers. This front is called the "Cold Front" and is generally identical with the squall line or trough. At the right we have the relatively warm southwest winds overrunning the colder air to the east, giving widespread cloudiness and precipitation. In the central figure, the line trending east and southeast from the low center shows the position of the warm front, while the cold front extends southwestward from the center of lowest pressure. Between the warm and cold fronts at and near which cloudiness and precipitation are in evidence, there is, in the United States, a region of warm air and relatively clear sky and sunshine, although cumulus clouds are to be expected because of conditions favorable to convection. It will be noted that a narrow band of showers occurs along and immediately behind the polar front. On and immediately ahead of the warm front, however, the area over which rain is falling is relatively broad, the rain being due to the forcing of the warm south and southwest current up over the cold, dense currents from the east and southeast, thereby producing adiabatic cooling. It will be noted further that on the warm front, warm surface air is replacing cold, and that on the cold front, cold air is replacing warm. What may be a cold front today may, therefore, become a warm front tomorrow and such we find occurs in certain cases. Cyclones develop,

increase in intensity for a while, and later die out. In the United States about 40% of the cyclones observed develop within its borders or over the waters immediately adjacent thereto. Cyclones frequently occur in families on lines and surfaces of discontinuity separating cold, polar air from warm, tropical air. The point where the development takes place is where a bend or wave develops in the line or surface of discontinuity, generally to the southwest of the anticyclone.

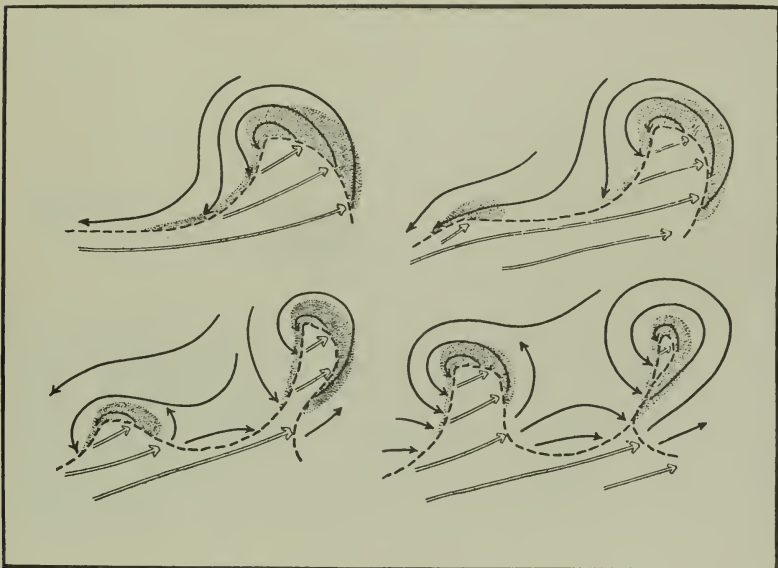

Figure 66. Progressive Stages of Occlusion, According to Bjerknes

When the cold front advances more rapidly than the warm front, they gradually get closer and closer together and finally meet, as indicated in Figure 66. The south and southwest current constituting the warm sector gives place to the polar air at the surface at first, gradually extending to greater heights until the supply of warm tropical air has been shut off completely. Such a process is called an "occlusion." Following the occlusion the Low generally decreases in intensity.

Regeneration or redevelopment takes place when a Low once formed; later increases in intensity.[3]

In this country meteorologists still think largely in terms of Highs and Lows as shown by surface isobars, but at the same time, they consider very carefully the positions and changes in position of the lines of discontinuity or "fronts" associated with them. In addition, a forecaster must envisage the wind structure, and as far as he is able, the temperature and humidity structure of the Highs and Lows. This applies not to the average High and Low but to the individual cyclone and anticyclone with which he has to deal. A consideration of all these elements has given him a firmer grasp of the situation and enables him more intelligently to explain the processes of cloud and precipitation formation and to forecast more accurately the occurrence of these phenomena.

Line squalls. In the preceding section we have discussed the fronts. At this time it is desired to invite particular attention to a phenomenon of the cold front, namely, the "line squall" which occurs in connection with well-developed trough formations. Perhaps the most exhaustive reference on this subject is to be found in a paper by M. A. Giblett,[4] which deals more particularly, however, with such phenomena as they occur in Europe. In another article,[5] published on the back of the Pilot Chart for the North Atlantic Ocean for March, 1929, phenomena of this kind occurring in the United States are discussed. The line squall is characterized by a sudden shift of wind attended by a squall ranging from 15 to 20 miles per hour (7 to 9 m.p.s.) up to as much as 100 miles per hour (45 m.p.s.). Another essential characteristic is a sharp fall in temperature; in fact, this is the physically important element. The line squall may extend for several hundred miles in especially well-developed cases, but frequently

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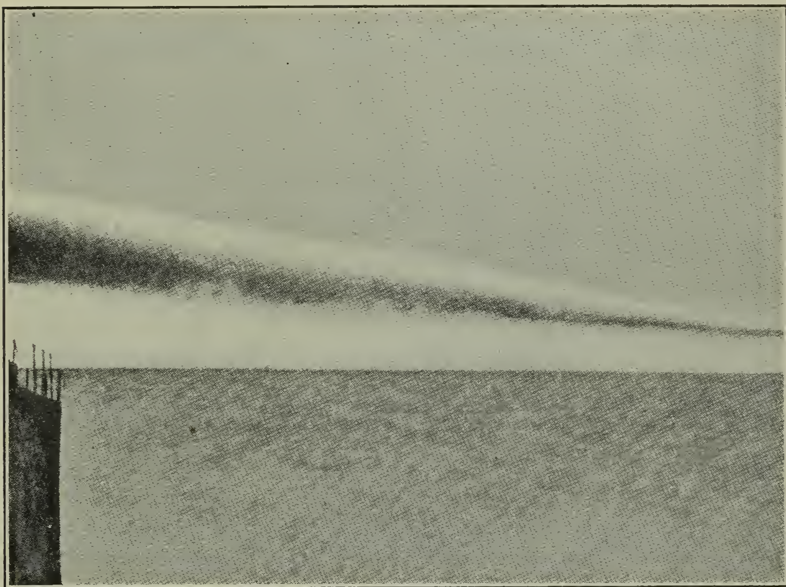
[3] An extremely interesting case of this kind is described in the *Monthly Weather Review*, Vol. 52, 1924, pp. 521-527, by J. Bjerknes and M. A. Giblett.

[4] "Line Squalls," *Journal Royal Aeronautical Society*, (198), 31; 509-549 (1927). (See also abstract in *Monthly Weather Review*, Vol. 56, pp. 7-11, January, 1928.)

[5] "Line Squalls," by R. H. Weightman.

is much less. The speed of advance has a wide range, the most usual limits being from 25 to 35 miles per hour (11 to 16 m.p.s.), but in some cases as great as 50 or even 60 miles per hour (22 to 27 m.p.s.). Line squalls including all degrees of intensity are quite frequent but for every severe one there are many of slight or only moderate intensity. The more intense type may recur at relatively short intervals of a day



Courtesy, Royal Aeronautical Society

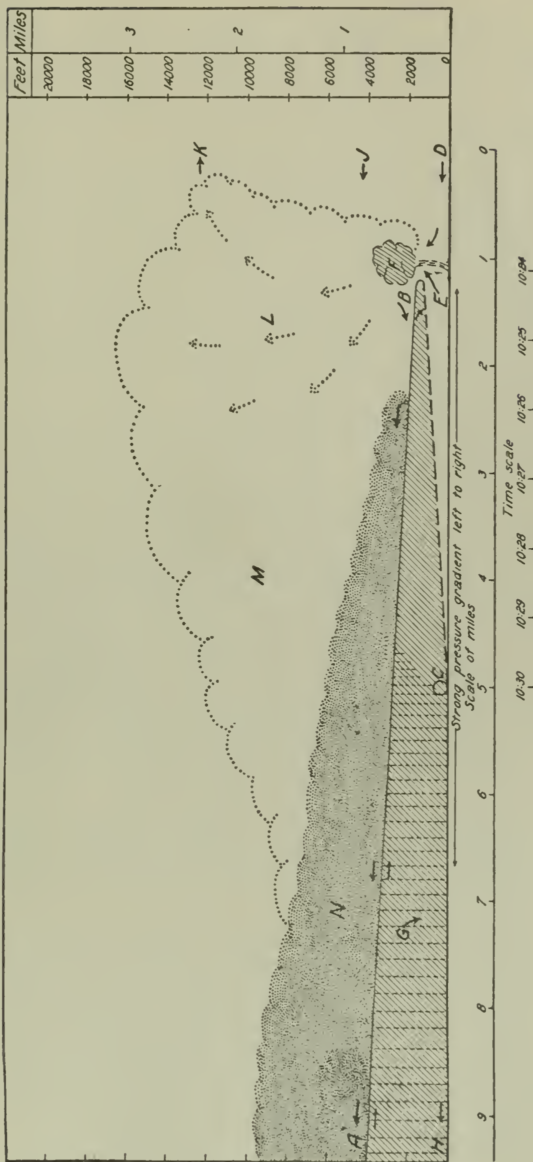
Plate XLIV. Line-Squall Cloud

or two, but more frequently a period of several weeks may elapse which will be relatively free from such phenomena. The violent motions peculiar to the line squall and the roll cloud are limited in most cases to the first 6,000 feet (1,800 m.) above the surface, but above this the usual intense vertical currents of thunderstorm clouds may occur up to 15,000 or 20,000 feet (4,500 to 6,000 m.) and in a few cases to even greater altitudes. The vertical currents in these well-developed thunderstorms often reach enormous velocities, judged

from the size of hailstones, in some cases exceeding 3 inches (76 mm.) in diameter. It is known from experiments that velocities of approximately 100 miles per hour (45 m.p.s.) are required to sustain stones of that size. The region of line-squall occurrence as related to the Highs and Lows is in the trough of the Low, where warm winds from a southerly quarter shift to cold winds from a westerly or northerly quarter. The shift at the surface is generally preceded by a typical line-squall cloud or "roll" cloud (see Plate XLIV) indicating quite clearly that winds at an elevation of 1,500 to 2,000 meters (4,900 to 6,600 ft.) have shifted to a westerly or northerly direction, while the winds at the surface remain for a short while still from a southerly quarter.

No complete survey of any one case at all heights has ever been made, but there are many fragmentary observations of various phases of the different cases. Piecing these together and combining them with non-instrumental observations and certain theoretical considerations, a picture of the essential features in the immediate neighborhood of the squall line may be obtained, as illustrated in Figure 67. In this diagram the horizontal and vertical scales are the same, so that a correct idea of the proportions is at once given. It should be borne in mind that the line squall is essentially a cold front phenomenon and that, unless cold air replaces warm air and also overruns it, line squalls would not occur. In the diagram the hatched area is a section of the cold wedge which is advancing to the right. Owing to surface friction the cold air is found farther advanced above the surface than at the ground itself, and the upper limit, *AB*, of the cold air, instead of continuing until it cuts the surface, is doubled back at the point *B* and meets the surface of the ground at the point *C*. This latter point is to be considered as marking the cold front at the ground.

The moment when the barometer begins to rise at the ground station is when the point *B* comes overhead and,



Courtesy, Royal Aeronautical Society

Figure 67. Section of Cold Front and Line Squall

To convert feet to meters, multiply by 0.3; miles to kilometers, multiply by 1.6.

as the denser air above the station increases in thickness, so the barometer continues to rise rapidly. It is on the passage of the point *E* that the squall commences and continues until a little after the passage of the point *C*. The wind shifts to a westerly quarter on the passage of the point *C*. The letter *F* in the figure indicates the position of the line squall or roll cloud. The average distance between the cloud and the wind shift at the surface is about 4 miles (6 km.). The time interval separating the two phenomena depends on the speed of movement of the whole system. If we assume a moderate rate, say 30 miles per hour (13 m.p.s.), the time interval would be 7½ minutes.

Conditions of this kind are most dangerous not only for airplanes but also airships. A local thundersquall can be circumnavigated, but a line squall several hundred miles in length presents a most serious problem. These phenomena sometimes move with moderate speed, but frequently attain speeds of 40 to 60 miles an hour (18 to 27 m.p.s.). While the squall cloud occurs on the average at a height of roughly 1,500 to 2,000 meters (4,900 to 6,600 ft.), when thunderstorms occur the turbulence no doubt extends twice as high. The idea of flying over a line squall is therefore attended by great hazards if not being impossible for the average plane.

Local forecasting. The following excerpts are taken from notes furnished by Dr. Charles F. Brooks, on the prognostic value of clouds:

1. Those who are so situated that they cannot receive the U. S. Weather Bureau's forecasts either directly by radio or indirectly from a distributing center, by telephone, newspaper or mailed weather map can nevertheless use local indications to good advantage in anticipating weather changes. Observations of atmospheric pressure, winds, clouds, sky colors, temperature and humidity, are all of value as prognostics. During a storm, changes in the character of the falling snow or rain also herald different weather. The observer who is without instruments is by no means helpless, as is evident from the local success attained by those who closely watch and remember the

changing aspects of the sky. Unfortunately many rules that apply at one place may not be of value at another. He who keeps his own record of clouds and weather can soon discover useful prognostics for important changes.

2. Squall prognostics, sharp mammato-cumulus (a cloud with mammillated lower surface, often occurring in connection with severe local storms) a low arch cloud, or the approach of a solid-looking rain-front. The squall from a thunderstorm reaches forward usually not more than 5 miles (8 km.) from the rain-front, and it usually blows out perpendicularly from the rain-front. Squalls occasionally occur in strong southerly winds when they come down to the surface.

3. Cloud movements at high velocities from southerly directions, may indicate forced ascent and coming rain, but the presence of such winds even at moderate elevations does not necessarily indicate similar winds for the surface. Such winds are usually considerably warmer than the surface air, and therefore, there is little tendency for a strong southerly wind to come down. On the contrary, strong northerly winds and hard-looking cumulus or strato-cumulus clouds at moderate elevations, are practically infallible signs of a coming gale at the surface, for although at first the temperature gradient is not as great as the adiabatic, only a few hours of such air movement from the cooler north will suffice to produce a tendency to a superadiabatic gradient, with the accompanying rapid interchange of air between the surface and the overrunning cold wind. The appearance of gradually thickening cirro-stratus, then alto-stratus with heavy lines converging in the direction from which they come indicates that an intense cyclone is approaching and that in the normal course of its movement gales will be upon the observer.

4. Morning stratus clouds from the south usually are a prognostic of a marked rise in temperature, for they are formed by the mixture of warm, moist air aloft with colder, surface air. Alto-cumulus clouds in the evening when the wind is south are more likely to last all night, or to increase than more or less similar clouds when the wind is northwesterly, for in the first case it is usually the southerly wind that is responsible for their formation, while in the second, such clouds may be merely the leftovers of flattened tops of convectional clouds formed during the daytime convection from the surface.

5. The speed of movement of the high cirrus (white, feathery, or hairy) clouds is usually a good index to the changeableness of the weather. When these clouds are moving fast, foul weather, i.e., wet or windy weather or both and a sudden change in temperature is likely to follow soon after fair weather. When they are moving very slowly

or seem to be standing still, settled weather is to be expected for at least a day or two. Movement of cirrus clouds from the south or southeast should be looked on as cautionary signals, for high clouds from this direction are usually flowing out from the top of an intense cyclone or West Indian hurricane. Another hurricane cautionary warning is the occurrence of a brilliant fire-colored sunset light reflected from the undersurface of clouds for a period of a few minutes shortly after sunset.

6. Of more immediate interest is any advance information as to how soon a brewing thunderstorm may strike. In a period when afternoon thunderstorms are occurring or are expected, the direction of motion and the apparent speed of the fleecy, alto-cumulus clouds should be noted. If, for example, the motion is from the west-northwest, any large cloud heaps or arched tops of thunderstorms in that direction should be watched closely. If the alto-cumulus clouds have been moving fast, shelter should be sought soon, but if they have been going slowly a distant storm may not arrive for 2 hours. Furthermore, if a large thunderstorm is seen approaching apparently from the north-northwest, even if the alto-cumulus clouds have been observed moving rapidly from the west-northwest the storm is not likely to break as soon as might be expected, for the nearest portion of the storm is not coming toward the observer. Under such conditions, however, the squall will come from the northwest and is likely to prevail for an appreciable interval before rain begins.

7. In the early morning the occurrence of low clouds moving rapidly from any direction, but particularly when from northwest or north is a good indication of a day with strong winds from the direction from which the clouds are moving.

8. Slow cloud movements, especially of cirrus from easterly directions accompany and precede settled weather, usually dry. The entry of a northwesterly wind above a southwesterly wind at the ground is usually a precursor of a shower.

In Chapter 11 will be found information concerning local forecasting from the point of view of the large airships.

Weather proverbs. Long before the development of organized meteorological services, men engaged in pursuits the success of which depended largely upon the weather, noted the sequence of certain signs and indications and the changes in wind and weather that followed. In many cases they

expressed these in poetic form as "weather proverbs" or "maxims." Some of these are purely local in application and others are based upon mere coincidence, such as the fiction that a rainy St. Swithin's Day is followed by a rainy period of 40 days. Many others, however, are of more or less universal application and have stood the test of critical analysis, such, for example, as those connected with sunset colors, cloud formations, etc. Properly interpreted and applied, they constitute a useful aid in forecasting the local weather for short periods, one to four or five hours, ahead. Those having a sound physical basis have been assembled and analyzed by W. J. Humphreys in "Weather Proverbs and Paradoxes."[6] The reader will find much of interest in this little volume.

[6] Published by The Williams & Wilkins Co., 1923.

CHAPTER 11

AIRSHIP METEOROLOGY

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The fundamental differences between airships and airplanes in principles of flight cause important differences in their meteorological needs. The chapter on airship meteorology considers the weather subjects which apply especially to airship design and operation. There are three characteristics of the airship which give importance to these weather subjects. They are the ship's great size, its long cruising radius, and its use of static lift. Because of the ship's size and its large exposed surface, the total pressure exerted on it by the wind is large. This force, relatively unimportant when the ship is in flight, may become of prime importance when the ship is being handled on the ground during docking or undocking, or when it is riding to the mast. Precautions must be taken to guard against surprise by a wind which would place excessive strains on the ground handling gear, the mooring equipment, or the ship. The situation is analogous to the effect of tides and currents on a surface vessel while it is being docked. Another important subject deals with the wind accelerations which occur in strong gusts and in other sharp discontinuities in air currents. Sometimes the forces from these place force moments of considerable magnitude on structures as long as an airship. Extreme wind accelerations persisting for periods longer than a few seconds are important factors, not only on the ground, but also during flight.

An airship's fuel supply permits it to remain in the air several days. It is essential to have forecasts of wind and weather a day or more ahead in order that weather conditions which will influence the flight can be taken into account in the navigating plans. Forecasts enable the navigator to make suitable schedules and to insure final arrival at an airship mast or dock equipped to handle refueling and other servicing.

There are several meteorological elements which affect the static lift of an airship. A few degrees change in temperature through its influence upon density of air and buoyancy alters the lift of a large, rigid airship several thousand pounds. In flight such changes are balanced by dynamic lift, but on the ground they in part determine the number of passengers and amount of freight carried. Humidity has a part in determining the lift through its influence upon density and upon moisture content of gas cells and fabric cover. Fog, rain, and snow similarly affect lift. The water from a heavy rain sometimes increases the load of an airship by thousands of pounds. Compensation is made for this when necessary by the discharge of ballast. When the weather clears and the ship dries off, the increasing free lift is reduced by valving gas. To avoid discharge of ballast and gas, when practicable the ship detours a meteorological distribution in which it alternately encounters rain and sunshine. Forecasts of these conditions assist in planning such detours. Fog, low clouds, and other forms of poor visibility interfere with airship navigation as they do with other aerial navigation, although the airship's ability to "lie to" in the air, or to proceed slowly, until conditions improve, greatly reduces their menace. While not all of the weather factors to which reference has been made have direct bearing on the safety of airship operation, all do have important places in the calculations entering into effective and economical airship operation.

Wind Structure

The surface wind. There are three different conditions constituting accelerations or discontinuities in the surface wind which are of particular interest in airship operation, especially in handling at the mast or on the ground.

(a) Wind gusts—rapid local fluctuations in wind velocity and direction over brief time periods usually expressed in seconds. These fluctuations occur in rough, non-periodic cycles in all winds of perceptible velocity.

(b) Wind squalls—local changes in wind velocity and direction, without regularity in form or occurrence, and usually associated with shower or thunderstorm clouds, although not always. These wind changes are commonly the result of vertical currents set up in shower clouds or of a mass of colder air which has developed from evaporation of precipitation in showers. In behavior these wind discontinuities are similar to general wind-shift lines. In contrast to wind-shift lines, they usually mark the arrival of a temporary wind condition lasting less than an hour and often only a few minutes.

(c) Wind-shift lines—not local but general changes in wind direction and velocity occurring at the boundary surface between air masses with different temperature and humidity characteristics. These are relatively infrequent and usually without regularity in intensity and frequency. In form of the alternating land and sea breeze, they may be regarded as occurring twice daily in many coastal regions, but in their more general form of boundary surface between "polar" and "equatorial" air in the Lows of temperate zones, they are less frequent. A wind-shift line is followed by a wind régime which usually continues many hours and perhaps days.

Gusts. It is necessary to know the characteristics of wind flow, that is, the forms of gust "waves," their extent vertically and horizontally, and their duration, for use in detailed studies of the forces imposed on objects by the wind.

Briefly, the space and time accelerations of wind gusts must be known. Since gusts are the effect of turbulence in the air due primarily to friction between the lower air layers and the ground or objects on the ground, it cannot be expected that they will show regularity in characteristics. Their "structure" has been studied by recording anemometers. Measurements by hot wire anemometer [1] have shown that superimposed on the perceptible gusts are innumerable ripples, the periods of which are small fractions of a second.

Records obtained in coastal winds from the sea indicate an average periodicity of approximately 0.2 second for these ripples. They are accompanied by sharp but momentary changes in wind direction. For example, during one series of fluctuations lasting but one-half second the wind velocity changed abruptly from 31 miles per hour to 37 (14 to 16 m.p.s.), back to 31 and up to 42 miles per hour (19 m.p.s.), accompanied by variations in wind direction vertically amounting to 16° inclination above and below horizontal. In another case, the wind velocity changed in one-half second from 26 to 42 miles per hour (12 to 19 m.p.s.), with fluctuations in the vertical from +10° to −16° to +13°. Among the most extreme rates of change in wind so far measured are changes at the rate of 70 miles per hour (31 m.p.s.) per second in velocity and 180° per second in direction. It should be emphasized that these rates were maintained only fractions of a second and that there are no reliable records available showing *sustained* changes totaling 70 miles per hour (31 m.p.s.) in one second, or 180° in one second. If such extreme changes occur outside of tornadoes, they are probably infrequent or of very limited extent. If the extreme wind accelerations shown in some of the momentary ripples were maintained over periods of several seconds, they would impose serious forces upon aircraft. But their duration in gusts is so brief that their

[1] "Studies of the Accelerations and Angular Velocities of Natural Winds," by Hagnenard, Magnan, and Planiol, *Bulletin Technique*, No. 49, June, 1928 (in French). These measurements were made in a study of vertical components of wind applying to gliding flight.

total force is not sufficient to overcome the inertia of sizable objects.

Turning to consideration of wind accelerations in perceptible gusts which reach forces having practical importance,

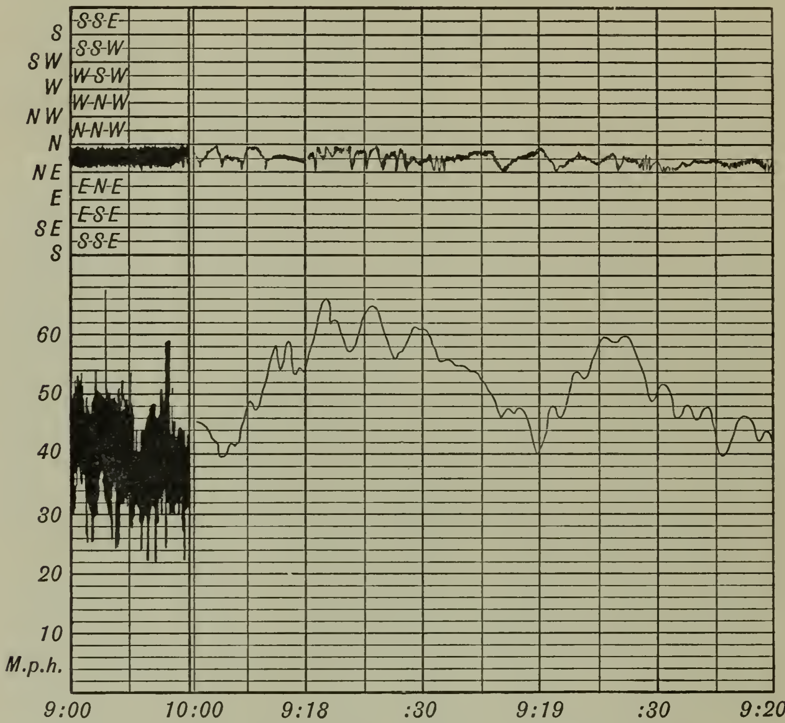

Figure 68. Wind Fluctuations as Shown by Gust Recorder

Heavy portion (left): Time scale, 0.6 inch (15 mm.) per hour. On right: Two and one-half minute record of same wind at time of maximum gust. Time scale, 1.2 inches (30 mm.) per minute. To convert m.p.h. to m.p.s., multiply by 0.45.

there is shown in Figure 68 the record of a wind of average velocity about 40 miles per hour (18 m.p.s.) as traced by an anemobiagraph. This instrument is essentially a recording Pitot tube. The head of the tube is turned into the wind by a vane. In studying gust data it must be kept in mind that the records made by most anemometers are only approximate. The difficulty in all anemometry is the construction of a recording

device rugged enough to withstand strong winds and yet sufficiently light to avoid errors from inertia and friction. Probably the most accurate gust measurements are those made by the hot-wire anemometer, some of which were mentioned in the preceding paragraph. Owing to technical difficulties in operating, there are comparatively few records from this type of anemometer. The pressure-tube anemometer, or anemobiagraph, in most common use as a gust recorder may have appreciable errors. One is failure of the vane which is to leeward of the Pitot tube orifice to keep the latter into the instantaneous wind. Others are friction in the recorder float and varying lag in its response to changes in wind pressure. The errors from these sources are ordinarily not of practical importance, especially in cases when changes in wind velocity are sustained and without violent directional fluctuations. There is no doubt that the instrument fails to record momentary fluctuations accurately. Referring to Figure 68, the left portion shows a section of the record for 1 hour during which the ordinary time scale of about 0.6 inch (15 mm.) per hour was used. The right portion shows a 2½-minute section of the same wind on a scale of 1.2 inch (30 mm.) per minute (0.02 inch [0.5 mm.] per second). It includes the maximum gust of 67 miles per hour (30 m.p.s.) shown at one point on the left. This figure illustrates the irregularity in velocity and direction always present in the surface wind, the amplitude of the irregularities being roughly proportional to the average wind velocity.

Gust forms. Anemometer records show that increases of wind at the rate of 10 miles per hour (4 m.p.s.) in a second with this rate maintained for 2 or 3 seconds are not uncommon. Increases of 30 miles per hour (13 m.p.s.) in 4 seconds have been recorded with part of the increase at the rate of 40 miles per hour (18 m.p.s.) per second. The velocity reached at the end of the acceleration is often held for 5 to 10 seconds followed by a rapid deceleration lasting a second

or two and then an acceleration to a velocity often higher than that reached in the first surge. These double surges covering 20 to 40 seconds constitute a not infrequent form of gust. During this time period there are in many cases abrupt changes of 60° in horizontal direction and 30° in vertical direction. Changes of this magnitude often occur within a period of one second. Usually, but not always, such abrupt changes are momentary and are followed by quick return to the previous direction, or by sharp, rapid oscillations about this direction. There is some tendency for oscillations in direction to be most pronounced at the beginning and ending of gusts. As

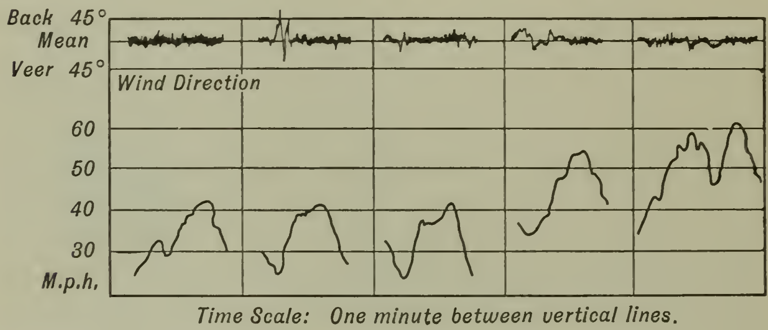

Figure 69. Portions of Dines Anemobiagraph Records Showing Five Different Gusts

To convert feet to meters, multiply by 0.3; m.p.h. to m.p.s., multiply by 0.45.

is to be expected, the most abrupt shifts in direction are usually those which make the surface wind conform more closely to the wind direction at low altitudes aloft. Figure 69 gives copies of other forms of gusts as recorded by anemobiagraph. The gust records illustrated in this chapter were made at Lakehurst, N. J. The instruments have an open exposure approximately 70 feet (21 m.) above the ground on level terrain composed of sandy soil. This site probably does not represent abnormal conditions as regards factors contributing to gustiness. The changes in wind direction during gusts are important in connection with ground handling

of airships because it is the sudden side gust that exerts the most pressure on the ship and places heavy strains on handling lines and mooring gear. The vertical and horizontal extent of the gust also have much to do with the total force imposed on the ship by the gust.

Satisfactory data on the space characteristics of gusts have not been presented although this subject of gust "dimensions" is one of much interest among engineers. It is known that a well-defined gust often extends 1,000 feet (300 m.) or more along its front, that is, in the horizontal direction perpendicular to the wind. A simple computation based on the wind velocity of a gust and its duration at a point shows that its other horizontal dimension, parallel to the wind, is often more than 1,000 feet (300 m.). From rough observations of effects of gusts on objects on towers, their vertical extent can evidently be several hundred feet at least. But they doubtless show wide variations in lateral and vertical extent like the atmospheric eddies which give rise to them. It is certain that the effects of many gusts are limited to distances of a few yards. Studies of smoke drift have shown that small gusts sometimes take the shape of vortices for short distances, and that in other gusts there is a circular motion about a horizontal axis. The latter appear to be more frequent in the wind above the immediate surface layers. They have been explained as cylindrical rollers generated between the surface wind layers and the faster layers aloft. They maintain their identity for short distances only. The rates of translation of gusts are of interest in connection with design of warning devices surrounding airship masts. It is usually accepted that gusts travel for short distances at the average speed of the wind 100 or 200 feet (30 to 60 m.) above the ground. In all of the characteristics under discussion, little regularity is to be expected. An individual gust is continually changing in form, size, intensity and rate of movement. Records indicate that it soon loses its identity.

Gust frequency and amplitude. The frequency and amplitude of gusts are subject to such wide variations that average values are of little use except as a rough conception. The averages change greatly with small changes in the defining values. With reference to velocity, it has been found that well-defined gusts consisting of velocity increase, regardless of actual velocity, exceeding 20% of the mean wind have an average frequency of 30 to 40 per hour. Gusts, with increase regardless of actual velocity, exceeding 40% of the mean wind average 10 to 20 per hour. Gusts, with increase regardless of actual velocity, exceeding 60% of the mean wind are relatively infrequent, usually less than 1 per hour except in light winds. Records of the British Meteorological Office show that gusts exceeding 75 miles per hour (34 m.p.s.) measured by anemobiagraph occur only once or twice per year in the stormiest parts of the British Isles and less than once in 5 years in the least stormy parts. Fluctuations in wind direction are even less periodic than those in velocity. Small but perceptible fluctuations have average frequencies as high as 30 to 60 per minute. More marked fluctuations of at least 15° or 20° variation from the mean direction average from 2 to 5 per minute. The amplitude of velocity changes in perceptible gusts is usually from 25% to 50% of the mean velocity. The maximum gusts reach velocities with average values between 50% and 70% in excess of the mean velocity. Measurements of gustiness in the United States, England, and Germany have shown approximately the same values for amplitude of average gusts and maximum gusts. For example, if the mean wind is 30 miles per hour (13 m.p.s.) the velocity reached in most of the gusts is between 40 and 50 miles per hour (18 to 22 m.p.s.) and in the maximum gusts, usually between 50 and 55 miles per hour (22 and 25 m.p.s.). The gustiness factor, usually defined as the ratio between the gust amplitude (gust peak minus lull) and the mean wind, is ordinarily greatest in the afternoon. The amplitude of wind directional changes

in gusts is usually less than 45°, but occasionally there are abrupt swings of 90° to 135°. These are usually momentary in duration.

In the accompanying Table 14 are listed some of the changes in wind direction and velocity observed in gusts in various localities. The first two examples show extreme accel-

TABLE 14. CHANGES IN SURFACE WIND DIRECTION AND VELOCITY IN GUSTS

(To convert m.p.h. to m.p.s., multiply by 0.45.)

Example No.	Average Wind Velocity m.p.h.	Wind Vel. Increased from m.p.h.	Time Inter-val sec.	Greatest Rate of Change in 1 sec. m.p.h.	Gust Avg. Vel. and Duration m.p.h.	sec.	Accompanying Direction Changes: Degrees cw. or ccw.	Time Period sec.	Location
1	25	26 to 46	0.4	50.0	–	1			See Text
2	25	26 to 40	1+	70.0	35	2	Stdy.		See Text
3	35	31 to 49	2.0	9.0	40	65	20 cw.	60	Lakehurst
4	30	35 to 47	1.5	8.0	40	10	60 ccw.	1	Lakehurst
5	30	40 to 51	2	5.5	45	15	45 ccw.	1	See Text
6	40	27 to 45	4	4.5	42	90	30 Var.	2	Lakehurst
7	35	20 to 42	10	2.0	40	180	Shftg.	See Text	Lakehurst
8	52	Max. 112 Approx.							British Isles

erations measured by hot-wire anemometer. It is to be noted that these accelerations held only for a fraction of a second and the terminal velocities were less than 50 miles per hour (22 m.p.s.). The remaining examples are gusts which accompanied homogeneous winds of various velocities. They were measured by pressure-tube anemometers to which the comments in an earlier paragraph apply. Between examples 4 and 5 there was a period of only 25 seconds. The direction backed 60° with the first gust, veered 50° in the next 20 seconds and backed 45° with the second gust. The average decelerations after gusts are apparently of somewhat smaller magnitude than the average accelerations. Only one or two of

the cases listed in the table represent extreme conditions. Most of the cases were selected to show a variety of gust conditions. They consist of moderately strong gusts which are not uncommon.

Causes of gusts. That gusts have the appearance of being largely accidental in character is understood when their principal causes are considered. Surface friction which is the chief cause varies with type of terrain. It is least over water. Therefore, ocean winds are commonly smoothest. Friction is greatest over rough country or near tall buildings,—there gustiness is greatest. These sources of gustiness are aided during the day by convection which results from heating of the ground. The temperature distribution in the particular air mass constituting the wind is a factor. If it is a north wind with temperature lapse rate in the lower layers near adiabatic and is bringing colder air, the lagging of the surface layers will cause the temperature to decrease more rapidly aloft than it does near the ground. This results in instability from the potentially denser layers above and leads to the breaking through of the air from above, giving the bursts or "surges" of downward gusts which characterize a cold north wind. A south wind, on the other hand, is usually slightly less gusty in velocity because the rapidly moving upper layers bring warmer air and build up a thermal stratification which is stable. It has been observed in various regions that fluctuations in wind direction in southerly winds are slightly greater than in northerly winds of similar velocity. This is noticeably characteristic when in proximity to a secondary depression and before development of squally conditions. Gustiness is less at night than in the day both because convection from the sun's heat is absent and because vertical stability is further increased by the temperature inversion built up by radiation from the ground. This applies to winds over the land. Further discussion of causes of gustiness and turbulence in the surface wind is given in Chapter 4.

Gusts aloft. The foregoing remarks and data apply to surface winds. Above 500 feet (150 m.), gustiness in a homogeneous wind stream diminishes rapidly with altitude. Studies in England have indicated that the gustiness at 3,000 feet (900 m.) decreases to about 25% of its surface value. This refers to gustiness in the sense in which it applies to surface winds. Other forms of turbulence such as that resulting from convectional currents often produce effects on aircraft similar to gusts. This type of discontinuity in air currents is discussed in later paragraphs.

Wind squalls. Usage of the word squall is not uniform. The word is often employed to describe an unusually severe gust lasting for a minute or more. It also is used to describe the increase in wind velocity and change in direction resulting from the local circulation peculiar to thunderstorms, heavy showers, and cumulus clouds with strong vertical circulation which extends to the ground. It is in this sense as distinguished from a gust, a brief wind increase in the general wind stream, that squalls are of special interest to aviators. This is the meaning intended in this chapter. The wind changes which characterize squalls differ in several respects from the wind changes in gusts. Squalls in the sense used here mark discontinuities in *air masses,* some large, some very small. Gusts, on the other hand, are usually rough cycles in a homogeneous air mass moving "steadily" as wind. There is no approximate relation between the maximum velocity in the squall and the mean wind velocity as is the case with gusts. Squalls are essentially changes in wind direction, either temporary or general, usually accompanied by increased wind velocity for at least a brief period. Gusts are essentially wind velocity fluctuations often accompanied by temporary changes in wind direction. The burst of wind on the front of a squall can give the most violent wind accelerations to be found outside of tornadoes. The wind direction shifts may be very large, sometimes exceeding 180°. The initial squall velocity

often continues for a few minutes. The wind following the burst of the squall and representing a new air mass continues for appreciable periods, occasionally only a few minutes but usually for many hours. If it is a local squall, its intensity depends upon the degree of development of the vertical currents or the cold air mass, sometimes both, which it accompanies. If it is a line squall, its intensity depends, in addition to the above, upon the contrasts in temperature and humidity of the air masses bounded by the wind-shift line. Clearly, then, there is no sharp distinction between the winds characterizing the front of a squall and those marking the arrival of a wind-shift line. The two often occur closely together, or merge entirely. Usually the discontinuities in a wind-shift line are better defined and more severe than those in a local squall, but it not infrequently occurs that local squalls develop into severe storms with wind changes equal in violence to those of any line squall. Since they so closely resemble each other, the wind changes on the fronts of squalls and wind-shift lines will be discussed together. Examples are given in Table 15.

Other squall characteristics. Usually a wind squall is accompanied by typical clouds which give visual warning of its approach. Under certain circumstances, for example along coasts the topography of which favors arrival of the sea breeze in an abrupt form, or in mountainous regions in which cold air may accumulate until it bursts down upon adjacent lowlands, a squall wind of violence may arrive without condensation of moisture and formation of a warning cloud. This type of squall, known as a white squall, requires attention in the operation of aircraft because it may cause serious difficulty in the air as well as on the ground. Another characteristic which is of interest in connection with ground handling of airships is the tendency for gales or strong winds to diminish in the form of a series of long-period lulls and peaks which in some ways resemble squalls. There are often three or four cycles in such a series, each cycle occupying from 30 to 60 minutes

with the amplitude diminishing in each succeeding peak. Their importance lies in the fact that the lull beginning the first cycle may be mistaken for a permanent decrease in the wind, and the occasion taken to attempt docking or undocking an airship with consequent risk of damage by the next squall. The first lull usually continues for 15 to 30 minutes, rarely longer than an hour.

Table 15. Changes in Surface Wind Direction and Velocity in Squalls and Wind Shift Lines

(To convert m.p.h. to m.p.s., multiply by 0.45)

Example No.	Average Wind Velocity	Wind Vel. Increased from	Time Interval	Greatest Rate of Change in 1 sec.	Gust Avg. Vel. and Duration		Accompanying Direction Changes		Type	Location
							Degrees cw. or ccw.	Time		
	m.p.h.	m.p.h.	sec.	m.p.h.	m.p.h.	sec.		sec.		
1	10	8 to 30	20	5		30	180 cw. 70 ccw.	30	Squall	Lakehurst
2	20	5 to 24	5	5		90	135 cw.	5	Thunder squall	Lakehurst
3	20	24 to 37	5−	4		60	90 ccw.	4	Thunder squall	Lakehurst
4	16	18 to 45	80±	4			195 cw.	Rapid	Thunderstorm	Boston
5		0 to 35	10−	5		60	90 cw.	1	Line squall	Lakehurst
6	18	16 to 48	60	4	40	60	115 cw.	120	Line squall	Lakehurst
7	25	32 to 74	120	3	60	40	90 fluc.	Rapid	Line squall	Lakehurst
8	17	19 to 100	120−		70±	60±	20 cw.	Slowly	Thunderstorm	Dist. of Col.
9		4 to 18	10−				10 cw.		Thunderstorm	Lakehurst
10		25 to 59	8−			60	45	1	Thunderstorm	Lakehurst
11	30	30 to 40					150 cw.	30	Line squall	Pensacola
12	30	to 200 (Est.)		15+			180	20	Tornado	

Importance of wind shifts. Wind shifts are of importance in airship operation because of the forces which they impose on the side of the ship. The wind rarely exerts excessive pressure on the nose of an airship. The ship is designed to withstand large forces from dead ahead, and only gale winds give forces of serious magnitude. Even these are important only when the ship is at the mast or on the ground.

In flight, forces from winds directly on the nose of an airship seldom reach serious values. When a wind shift occurs within a period too brief for the ship's nose to be turned into the newly arrived wind, the forces on the side of the ship may become large. This is true not only in the air, but especially when the ship is moored, or is being docked or undocked. Its importance is apparent when one recalls that if an airship is 800 feet (240 m.) in length, its tail describes a circle about 5,000 feet (1,500 m.) in circumference in moving around a mast to which the nose of the ship is moored. If the ship is headed into the wind, and the wind direction changes 45°, the tail must move about 600 feet (180 m.) to place the nose again into the wind. It requires appreciable time to overcome the inertia of the ship and move it through this distance.

Wind-shift lines. The most important wind-shift line is that which marks the arrival of the cold front of a cyclone (Low). This is the boundary where the colder, drier, and therefore denser air from the approaching High displaces the warm, moist air, in the right-hand portion of the Low. The wind-shift line is usually most severe when the Low is of the type called a V-shaped depression—when the trough line is shaped like a "V." Under favorable circumstances the cold northerly wind underruns the warm southerly with a boundary so sharp as to give a wind shift from southwest to northwest within a very few seconds and an accompanying velocity increase from 10 or 15 to 50 miles per hour (4 or 7 to 22 m.p.s.) and occasionally to 75 miles per hour (34 m.p.s.) within 4 or 5 seconds. The mass of cold air sweeps over the land like a wall of water. This is the formation which gives the abrupt changes in temperature not infrequently experienced in the temperate zones. The formation has numerous variations. In this extreme form it often causes violent convection, thunderstorms, heavy rain, and wind storms extending along a line hundreds of miles in length. Its movement of translation is at right angles to its front. In this form it is called

a line squall. Figure 67 shows the structure of a typical line squall. It is discussed in more detail in Chapter 10.

The diagram of a line squall in Figure 67[2] shows a cross-section through the forward edge of the cold front and is drawn approximately to scale. The cold wedge is represented by the wedge-shaped portion between *B*, *E* and *H*. It advances over the ground in the direction to the right. The effect of surface friction is seen in the lagging of the cold air at the ground. Aloft it has advanced to *B*; on the ground it is at *C*. The squall is said to reach a station on the ground when the front portion at *B* is overhead. When this occurs the barometer begins rising and usually the surface wind becomes squally between this point and *C*. As the cold wedge deepens over the station the barometer rises proportionately. The 9-mile (14 km.) section of the cold wedge shown in the diagram passes a given station in about 10 or 15 minutes. A time scale representing the time of arrival of successive portions of the cold front at a given station is shown below the horizontal scale of miles. The upper slope of the boundary of the cold front is drawn at about the angle which it appears to have in many cases. After the first few miles, the slope of the front decreases as is evidenced by the slower rise in the barometer.

The arrows in the diagram were placed by Giblett to show the air currents with respect to point *C* in the front. They show the circulation within the line squall, not with respect to a stationary point on the ground. To obtain the motion observed from a station on the ground, the velocity of *C* must be added algebraically to the velocity at the points under consideration. At *D* the air is being overtaken by the cold wedge. As *D* and *E* draw close together, a vertical current is set up and if the dew-point is reached as the ascending air cools, a cloud forms at *F*. The air in the cold wedge near

[2] Diagram and explanation are based on an article by M. A. Giblett, published in *Journal Royal Aeronautical Society* (London), No. 198, Vol. 31, June, 1927.

B since it is advancing more rapidly than the lower layers, becomes colder and denser than the air below and therefore tends to form a descending current. This current, close to the ascending current at *F* may give a rolling motion to the cloud at *F*. This is the characteristic roll of the line squall. It is not always visible. As the warm air is forced up over the cold wedge, its cooling by expansion may cause formation of a nimbus cloud represented by the dotted portion *N* with rain as indicated by the dashed lines between *C* and *H* falling through the cold wedge. Often the warm air which rises at *F* is unstable with respect to the adiabatic rate for saturated air. In this case, condensation once started, is followed by more rapid ascent, by further condensation, and so on until a thunderstorm is formed as represented by *ML*. This depends largely on the character of the air encountered by the advancing cold wedge. In some places it is favorable for thunderstorm development; in others, it is not. There is a descending movement of air at *G* usually gentler than that at *B*, as the two portions *C* and *H* diverge. This descending current may, in the presence of heavy rain or snow, be intensified by cooling from evaporation and by friction with the down-rushing rain. The squall wind usually begins with arrival of *E* overhead. The shift is commonly from a southerly direction to a direction between west and north at right angles to the front. The squall usually continues with some intensity until the portion *C* with its fall in temperature arrives. Soon after this the wind steadies down approximately to the velocity of translation of the cold air mass behind the front.

Frequently in the summer, a local thunderstorm develops until it covers 500 square miles or more and produces a wind shift which, viewed from a single point on the ground has the appearance of a general line squall except that after the storm passes, the wind usually returns to its previous direction. The thunderstorm develops a cold air mass through evaporation

of the rainfall. This cold air underruns the warm air in front of the storm and sometimes has a sharp surface of discontinuity with wind accelerations quite as severe as a general wind-shift line. With reference to other wind-shift lines of limited extent, it will be recalled that brief description has been given of sea breezes and other winds resulting from temperature differences of local origin which, under favorable topographical conditions, act like wind-shift lines and cause squall winds. When a cold front *overruns* warm southerly air, the resulting instability and convection often develop thunderstorms very rapidly as the entrapped warm air below and the potentially denser air above change places. Cases have been noted short distances at sea in which the cold front, advancing more rapidly at an altitude of about 4,000 feet (1,200 m.) overran the warm air, its progress being marked by great surges eastward first in one place, then in another. The wind shifts and squalls developed in this manner are particularly dangerous to aircraft in flight.

Table 15 lists some of the wind changes which have been observed in connection with squalls, thunderstorms, and wind-shift lines. The data given in the table refer only to shifts in the horizontal wind, and not to the vertical currents in squalls and thunderstorms which are discussed in the next paragraph. The conditions represented by the examples in the Table are not infrequent. Wind shifts of this order of intensity occur in most portions of the United States. Many regions experience such severe storms several times a year, but for most regions their occurrence probably would not be more frequent than once or twice a year. Wind shifts are not peculiar to the United States. Most portions of the globe experience similar shifts in the form of line squalls or thunderstorms, although their frequency varies greatly in different regions. Line squalls and thunderstorms occur at any time of day or night, but they usually attain greatest intensity in the late afternoon or evening when the instability owing to local convection is

most pronounced. Interesting circumstances of the second and third examples in the table are their occurrence at night with the sky generally clear until the squall cloud arrived, and the wind shift through 270° within a period of about 5 minutes. They were part of the same squall. The wind increased from 5 to 24 miles per hour (2 to 11 m.p.s.), held that velocity between 1 and 2 minutes, then increased to 37 miles per hour (17 m.p.s.), in about 4 seconds. This velocity continued for about 1 minute. On the first increase, the direction veered 135°. During the next 90 seconds it backed 45° and at the beginning of the second velocity increase it backed 90° more to the original direction. About 2 minutes later when the velocity decreased to 15 miles per hour (7 m.p.s.), the direction backed 135° more. Examples 6 and 7 were also closely associated. The latter occurred 10 minutes after example 6. The eighth example illustrates an unusual sequence in which a very violent thunderstorm occurred more than 2 hours before the line squall and general wind shift with which it seemed to be associated. The winds in the thunderstorm were extremely violent and attained their full force within a few seconds after the first burst of the storm. The winds in the subsequent general wind shift were less violent. In the thunderstorm squall the velocity increased from 18 to 65 miles per hour (8 to 29 m.p.s.) within a few seconds, paused there momentarily then increased to 85 miles per hour (38 m.p.s.), and after another brief pause continued to an indicated velocity of 100 miles per hour (45 m.p.s.) or more. The direction changed little during the squall. The temperature fell abruptly about 20° F. (11° C.). When the general wind shift arrived two hours later, the wind which had declined to 4 miles per hour (2 m.p.s.) increased to 34 miles per hour (15 m.p.s.), and the direction changed 90° within a few seconds. Two and one-half hours later another thunderstorm with gusts to about 30 miles per hour (13 m.p.s.) occurred. Example 10 followed number 9 within a few minutes with the wind velocity less

than 18 miles per hour (8 m.p.s.), in the interval between them. The 12th example is an estimate of wind changes which must have occurred in tornadoes, the most violent type of local storm. It is undisputed that velocities in the tornado have exceeded 400 miles per hour (180 m.p.s.). The diameter of a tornado is usually only a few hundred feet. The rate of translation is between 20 and 40 miles per hour (9 and 18 m.p.s.). The values tabulated are the minimum values based on well-authenticated observations in certain tornadoes. The same values probably apply to severe waterspouts of tornadic origin.

Table 16. Wind Shifts Aloft

(To convert m.p.h. to m.p.s., multiply by 0.45; feet to meters, multiply by 0.3)

Wind Shift from	Wind Velocity		Observed Altitude	Time Period of Shift	Location
	Before Shift m.p.h.	After Shift m.p.h.	ft.	sec.	
SSE to NW	25 to 30	30–40	1,500	30	Florida
ESE to WNW	30	30	3,000	Abruptly	Oklahoma
SSW to NW	33	33–55	3,500	Abruptly	North Dakota

Vertical extent of wind shifts. Accurate measurements of the characteristics of wind shifts aloft are comparatively few. It is known that some wind shifts are relatively shallow. In many cases the southerly winds which precede the wind-shift line continue to blow at altitudes of only a few hundred feet after the surface wind shifts to northwest, eventually veering around to westerly very slowly. Observations of clouds have shown other cases, however, in which the winds aloft shifted about the same time as the surface wind, apparently within a period of a few seconds. It is quite certain that there are some wind-shift lines in which the shift extends to altitudes of several thousand feet and occurs very abruptly. Table 16 gives three cases of approximately correct measure-

ments of wind-shift lines aloft. The first was obtained by noting the time which elapsed while clouds and smoke in the different currents traveled between objects a known distance apart. The second and third were recorded during kite flights. These cases typify discontinuities which would impose serious stresses on aircraft structures.

Discontinuities in vertical currents. The most serious form of atmospheric discontinuity for aircraft during flight is that which occurs with strong vertical currents. When the boundary of a vertical current is sharp it imposes severe strains on aircraft structures longitudinally much the same as does a sharp wind shift. It also carries the aircraft upward or downward, sometimes hundreds of feet with disastrous results. If, as is usual, it occurs with a thunderstorm, there are the further hazards of hail and lightning. For airships moored to a mast, vertical currents, especially descending currents, cause much difficulty because of the near impossibility of preserving the ship's static equilibrium and avoiding excessive angles of inclination. Direct measurements of discontinuities in vertical currents are difficult to obtain. Estimates of the vertical velocities within the currents are fairly numerous, some based on direct observations, others on computations. They demonstrate that the currents, especially upward currents, sometimes attain very high velocities. They doubtless reach their greatest severity in thunderstorms and tornadoes. The processes involved in the formation of thunderstorms and vertical currents are discussed in Chapter 8. There are various sources of vertical instability in the atmosphere which result in convection. These sources and the thermodynamics of convectional processes are complicated.[3] Table 17 gives some of the observed and estimated vertical velocities in ascending and descending currents.

[3] These latter are discussed very briefly in "Graphical Thermodynamics of the Free Air," *Monthly Weather Review*, November, 1926, with references to further treatises.

Examples 1, 3, 5, 6, 7, 13, and 14 in Table 17 are based on records of instruments or observations which may be accepted as reliable. The computations expressed in examples 4, 8, 9, 11, and 12, the first three given by Simpson, the last two by Humphreys, are based on careful analysis of observed effects of vertical currents and without doubt express vertical velocities which have occurred. Examples 2 and 8 express

TABLE 17. VERTICAL VELOCITIES IN ASCENDING AND DESCENDING CURRENTS

(To convert m.p.h. to m.p.s., multiply by 0.45.)

Example No.	Character	Ascending or Descending	Vertical Velocity m.p.h.	Given Velocity Based Upon
1	Thunderstorm	Ascending	11	Record from kite
2	Clear air	Ascending	12	Airplane ascent (estimated)
3	Clear air	Ascending	18	Pilot balloon
4		Ascending	18	End vel. of largest raindrop
5	Thunderstorm	Ascending	22	Manned balloon
6	Thunderstorm	Ascending	22	Kite ascent
7	Squall	Ascending	24	Airship ascent
8		Ascending	35	Vel. req. for 2 cm. hailstone
9		Ascending	53	Vel. req. for 4 cm. hailstone
10	Shower	Ascending	55+	Airplane ascent (estimated)
11		Ascending	92	Vel. req. for 3 in. hailstone
12	Tornado	Ascending	100 to 200	Estimated (Humphreys)
13	Thunderstorm	Descending	6	Pilot balloon
14	Thunderstorm	Descending	11	Manned balloon

two of the very numerous experiences of airplane pilots. The values are probably correct but lack verification. A very large number of cases similar to those listed in the Table could be given. Apparently the first eight cases illustrate conditions that are rather common in heavy showers and thunderstorms. That this is true is evidenced by the large number of reports showing the approximate intensity of vertical currents which have been encountered in thunderstorms at one time or another by practically all types of aircraft—airplanes, balloons, and airships. Measurements and reports from foreign countries indicate similar conditions wherever thunderstorms occur.

Discontinuity limits. It is important to know whether the boundaries of currents such as those typified in Table 17 are so sharp that one end of an airship might be in a strong ascending current while the other end is in still air or in a descending current. Direct measurements are not available. Observations of development of cumulus clouds indicate that the boundary is often very sharp. Similar evidence is given by the action of cloud wisps in some line squalls and by the roll cloud of a typical line squall. These indicate the close proximity of ascending and descending currents. This conclusion is substantiated by the violent spinning motion imparted to airplanes which have gone into such a cloud. The portion between the strong updraft in the front part of a thunderstorm or line squall and the descending currents in the region of heavy rain certainly is a place of strong vertical currents in opposite directions within a very short distance. An indirect indication of the probable proximity of such currents is afforded by comparison with wind shifts at air mass boundaries. If the wind is blowing from the southwest with velocity 30 miles per hour (13 m.p.s.), and it shifts in 30 seconds to northwest with velocity 30 miles per hour (13 m.p.s.), the transition zone between the two currents must be not more than 925 feet (280 m.) in width. The two currents with respect to each other are blowing in opposite directions so that an airship passing directly across their boundary would experience a change in wind from south 21 miles per hour (9 m.p.s.) to north 21 miles per hour (9 m.p.s.) in a distance of about 900 feet (270 m.). Reference to Table 17 shows that wind shifts with approximately these characteristics have been observed. It seems very probable that discontinuities in vertical currents are often sharper than the value given in this estimation.

Other characteristics of vertical currents. Ascending currents attain much greater velocities than descending currents. Temperature, pressure, humidity, and density relations

underlie this fact. While a violent ascending current usually results in formation of a cumulus cloud, there are sometimes strong vertical currents without clouds. Under suitable conditions of temperature and humidity, a moderate convectional current in clear air will become a thunderstorm in 5 or 10 minutes. A very severe thunderstorm sometimes develops in an hour. That extremely intense vertical currents can be set up in a short time is shown by the rapidity with which tornadoes with their vertical currents in excess of 100 miles per hour (45 m.p.s.) are formed. Over land the late afternoon is the time most favorable for formation of thunderstorms and strong vertical disturbances in the air. Thunderstorms often extend to altitudes of 25,000 or 30,000 feet (7,500 to 9,000 m.) and strong vertical currents have been observed at altitudes above 15,000 feet (4,500 m.). The formation of hail in ascending currents is described in Chapter 8. Hail often damages the propellers and fabric of aircraft and in extreme cases this damage alone prevents the airplane or airship from remaining in flight. Lightning usually accompanies violent convection. In itself lightning is not often a serious hazard to aircraft. It must not be overlooked, however, that casualties from lightning have occurred, especially in free balloons. Definite rules have been formulated for minimizing the likelihood of lightning stroke when flying in the vicinity of thunderclouds. The fact that an aircraft is outside the thundercloud itself does not insure that it will not be struck by lightning. The necessity for aircraft to avoid thunderstorms cannot be too strongly emphasized. Successful flight through one thunderstorm is poor evidence that an airship or an airplane can fly through the next. Evidence is overwhelming that no aircraft can withstand the turbulence of some thunderstorms.

Other aspects of surface wind in relation to docking and mooring. A subject which may receive attention because of its particular interest in docking and mooring of airships is

the decrease in wind at night. Figure 70 presents curves showing typical cases under different conditions. Airships use this characteristic of the wind as surface vessels use a favorable condition of the tide for docking or sailing. The

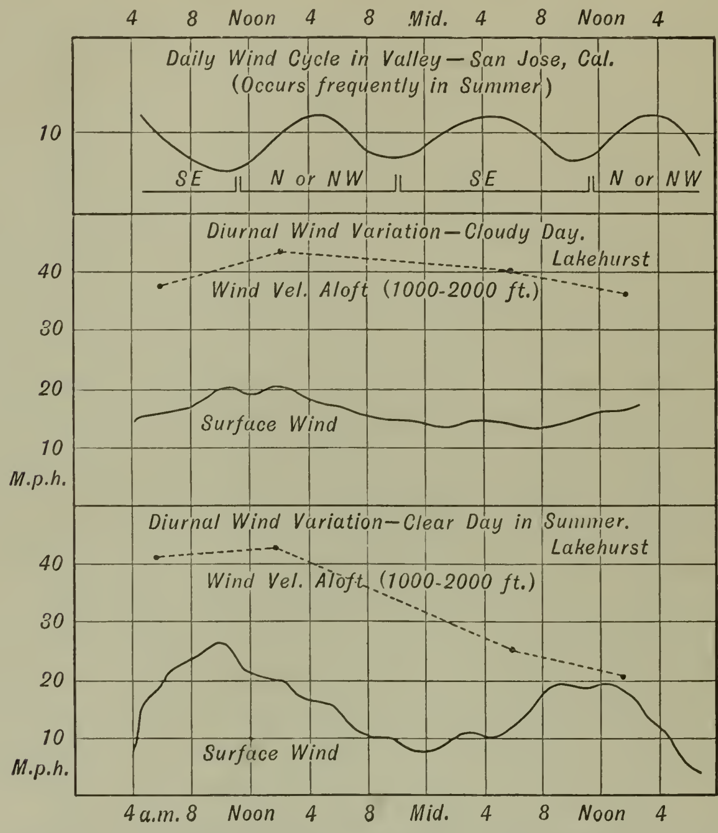

Figure 70. Illustrating Decrease in Surface Wind Velocity at Night
To convert feet to meters, multiply by 0.3; m.p.h. to m.p.s., multiply by 0.45.

decrease in wind velocity at nightfall is most marked on clear days. It is most rapid about sunset when the ground is cooling rapidly and an inversion of temperature is being built up from the surface. Usually the wind continues with decreased velocity during the night followed by marked

increase when the sun starts convection from the surface the next morning. Many times, however, there is a sunset lull after which the wind increases and remains at a slightly increased velocity during the night. The lull lasts for 15 to 30 minutes. The decrease in wind at nightfall is most marked close to the ground. Records from anemometers show that on a clear night in level country the wind at 175 feet (50 m.) above the ground averages 50% to 75% higher than the wind at 50 feet (15 m.), and 100% or more higher than the wind only 10 feet (3 m.) above the ground. The diurnal wind cycle shown in the upper portion of Figure 70 is due to the alternate influence of winds up the valley during the day, and winds from drainage of air down the valley during the night. It resembles a land and sea breeze and is most marked in summer. It is a type of wind particularly well suited to airship docking and undocking because of the regularity of its direction cycle and its frequent periods of low velocity.

The general subject of surface and upper winds as they apply to aerial navigation is discussed in Chapter 4. This discussion applies to airships as well as to airplanes. It is an important subject in airship navigation.

Air Temperature and Aerostatics

Air temperature is fundamental in aerostatics. At all times when an airship is air borne, whether in flight, at a mast, or in a dock, temperature changes are of importance. They may cause large changes in lift which must have prompt attention. The aspects of temperature most frequently considered, aside from those discussed in other paragraphs of this volume applying to all types of aircraft, are: (1) mean and extreme temperatures; (2) sudden changes in temperature; (3) vertical temperature distribution, especially in localities where the ship is landed or moored; (4) superheat, as defined later.

Temperature means and extremes. Data of mean and extreme temperatures are used in computing the probable lift of an airship during long flights, and the fulness to which the gas cells should be inflated. The mean temperature is the basis for average lift computations. The extremes show what the maximum variations from this average are likely to be. While the mean daily maximum and minimum temperatures for the month are often selected as the extremes to be used in these computations, it is somewhat more applicable to use the mean of the monthly maxima and the mean of the monthly minima. Use of the absolute maximum and minimum for the month (the highest and lowest ever recorded locally) gives variations so wide as to make the computations of little practical value. To obtain the temperature data for planning a long flight, the climatological publications of the countries to be crossed are consulted. In collecting and presenting these data, it is essential to note the meaning of each item and the method by which it was derived. The limitations of all meteorological averages are to be kept in mind. Means and averages are imaginary conditions employed in meteorology to present the facts of the weather concisely and systematically. The average or mean rarely is applicable to the weather at a particular time. Although it is common knowledge that the weather elements are characterized by variable, not by average behavior, the fact is often overlooked in interpreting weather averages. It is necessary also to have in mind the influences which introduce difficulties in comparing temperatures for different localities. These are chiefly terrain, lack of uniform exposures and differences in altitude. In considering these influences, each locality must be studied as a case by itself.

Mean temperature values are usually based upon continuous records over a 10-year period or longer. The mean for the same month varies from year to year, sometimes as much as 10° to 15° F. (6° to 8° C.). In eastern United States, the average daily range between the maximum and minimum is

between 15° and 20° F. (8° to 11° C.). This value is computed from the ranges for all days regardless of weather. On calm, clear days the maximum temperature may be 25° to 30° F. (14° to 17° C.) above the minimum due solely to local insolation. On cloudy days the range is often reduced almost to zero. When modified by the arrival of a new air mass, the range in one day is occasionally 40° to 50° F. (22° to 28° C.), infrequently more. This extreme change may be either an increase or a decrease. Ranges are usually greater inland than on the coast, and in valleys than on slopes and hilltops.

Sudden changes in temperature. Since abrupt temperature changes so modify the lift of an airship that immediate adjustment by means of ballast is often necessary, it is important to know what conditions give rise to abnormal temperature changes. The source of the most abrupt and widespread changes is the passage of a cold front. Usually these can be foreseen from a study of the weather map. Most cold fronts give rather mild temperature changes. The decrease in a 15-minute period, for example, is commonly less than 10° F. (6° C.), but changes in excess of this are not rare, and sometimes the decrease in the first quarter hour after the front has passed amounts to about 25° F. (14° C.). Aerological records show that temperature changes to altitudes of 3,000 or 4,000 feet (900 to 1,200 m.) are often similar in magnitude to those at the surface. Above these altitudes abrupt changes seem less frequent. Giblett states that sometimes there are rapid changes in temperature aloft amounting to 20° F. (11° C.) with little attendant change on the ground. The temperature changes which accompany other frontal formations are usually mild in comparison with cold front changes.

Very marked variations in temperature occur locally as a result of land and sea breezes, foehn winds, mountain and valley breezes, and certain other winds of local origin. These changes are sometimes quite as sharp as those with a cold front. Their extent varies greatly with locality. Sea breezes

are infrequently felt more than 30 miles (50 km.) inland. In most localities they reach inland only about half this distance. The decrease in temperature accompanying the sea breeze varies greatly. Along the middle Atlantic coast it is usually 5° to 10° F. (3° to 6° C.) within the few minutes after the sea breeze arrives. Occasionally it is 20° to 25° F. (11° to 14° C.). It is greatest in late spring when the ocean water is still cool. The foehn wind brings rapid rise in temperature in localities where topography is favorable. In a previous paragraph reference was made to the local "fronts" which are built up in heavy showers and thunderstorms. These sometimes bring temperature decreases of 20° F. (11° C.) or more on a hot summer day.

Vertical temperature distribution. Temperatures aloft bear a special relation to take-off and landing, particularly when the lapse rate is "abnormal," either extremely steep or with a large inversion. When the lapse rate is superadiabatic, the ship tends to become unstable as soon as its altitude is changed. In this respect the ship acts like a mass of air within a superadiabatic column. If it descends, its temperature which is increased dynamically lags behind the temperature of the surrounding air. It becomes heavier and descent is accelerated. If it ascends, its temperature does not cool rapidly enough to keep up with the gradient in the superadiabatic column. It becomes lighter and ascends more rapidly. Landing under superadiabatic temperature conditions is therefore attended by risk of too rapid descent. If the temperature lapse rate is isothermal, or there is an inversion, the instability is in the opposite sense. In ascending through an inversion, the airship loses lift rapidly. Momentum carries it past its equilibrium level and it settles toward the ground. The risk of settling too close to the ground can be avoided only by foreknowledge of the inversion and allowance for it in the take-off. If the ship is landing through an inversion, the temperature of its gas increases through dynamic heating

while the surrounding air temperature falls with decreasing altitude. The ship therefore gains lift. If the inversion is extreme, the ship must be forced through it by use of the motors, or by valving gas.

Steep lapse rates. The lapse rate aloft *in clear air* rarely exceeds the adiabatic by more than a small per cent. In violent storms, particularly of the line squall type, the superadiabatic rate may be much greater for short periods during the earlier stages of those storms. Information on the subject is fragmentary. Near the surface, usually only in the very lowest levels above the ground, the lapse rate on a hot summer afternoon may reach a value several times the adiabiatic. The most favorable conditions are black or sandy soil under a clear summer sky. Cold air over a warm ocean current occasionally gives superadiabatic lapse rates at sea. With reference to occurrence of lapse rates equal to or exceeding the adiabatic some distance above the ground, the conditions which most frequently give rise to these rates are air mixing in a turbulent wind, strong convectional currents and showers or thunderstorms. A few aerological records indicate that moderate superadiabatic rates may be set up by overrunning cold air.

Inversions. Temperature inversions are common at night when the ground cools more rapidly than the air. Figure 71 shows how an inversion develops over a flat, sandy region. It is most marked on clear nights when the wind is light. It is relatively shallow, usually only a few hundred feet in depth. In flat country the amount of inversion between levels 8 or 10 feet (2.5 to 3 m.) above the ground and 150 to 200 feet (45 to 60 m.) above is usually less than 10° F. (6° C.). Occasionally it is 20° to 30° F. (11° to 17° C.). In valleys the cool air settles to the lowest parts and the intensity and depth of the inversion are increased. There, inversions of 20° to 30° F. (11° to 17° C.) are not infrequent. The greatest inversion usually occurs about the time of the minimum tem-

perature on the ground. Inversions are not confined to the ground levels. They occur frequently aloft when a warm air mass flows over a colder air mass. Stratiform clouds and fog almost invariably are accompanied by temperature inversions. There are other indications by which the presence of inversions may be recognized. The nightly surface inversion is marked

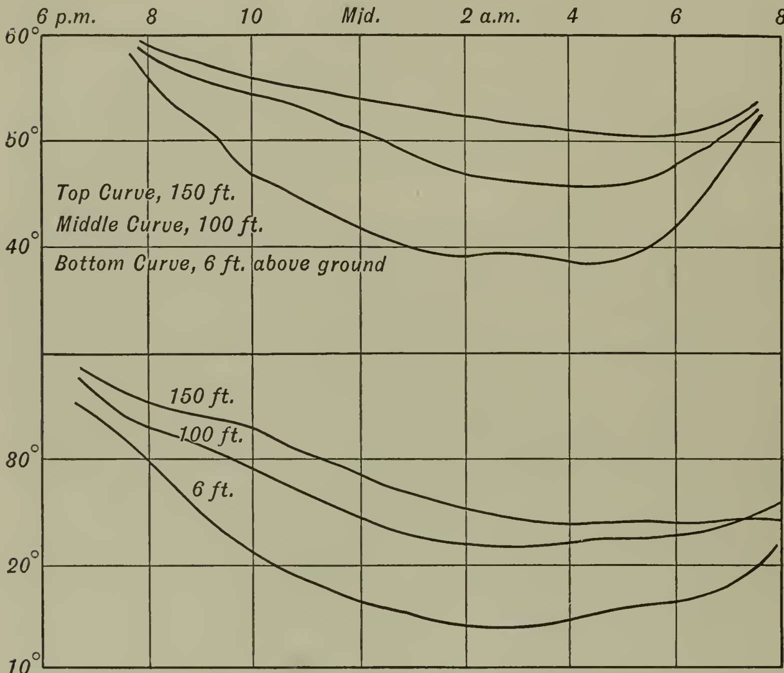

Figure 71. Thermograph Records Showing Development of Large Temperature Inversion on Clear Nights

Two cases with different temperature ranges. To convert feet to meters, multiply by 0.3; ° F. to ° C., subtract 32 and multiply by 5/9.

in the morning by the hazy or smoky appearance of the air. The upper boundary of the haze is the top of the inversion where the wind is usually stronger. The air above is decidedly clearer. Inversions are also indicated by the appearance of drifting smoke. The inversion causes the smoke to spread out in a sheet after ascending a short distance, or to take the form

of long, undulated streamers. This effect is often seen after a thunderstorm when there is a shallow layer of cold air on the ground. Among the most intense inversions recorded at rather high altitudes are those which occur over the coastal region of southern California. The greatest inversion recorded there during a period of several years amounted to 29° F. (16° C.). The temperature near the top was 96° F. (36° C.), and the altitude about 5,000 feet (1,500 m.). These inversions are most frequent from June to October. They extend over the ocean and seldom reach more than a few miles inland. A relation appears to exist between the character of the inversion and the coastal fog. Inversions aloft have less bearing on airship operation than those near the ground.

Superheat. The difference in temperature between the gas in an airship and the surrounding air is known as superheat. The word is also used in referring to the difference in temperature between the air in the hangar and the open air. Superheat is positive if the outside air is cooler; negative, if warmer. Detailed discussion of the subject belongs to the airship manual and the text book on aerostatics, but the general principles are of interest to the meteorologist. Superheat depends upon intensity of insolation, transparency of the air, proximity to reflecting surfaces, characteristics of the balloon or airship as regards absorption of radiation, ventilation, and so on. At an altitude of a few thousand feet balloons have been known to have a positive superheat of 40° to 50° F. (22° to 28° C.). The superheat of a rigid airship during the forenoon of a clear day is usually about 10° F. (6° C.). The resulting decrease in density of lifting gas gives an appreciable increase in useful lift. It is often made use of for taking off with maximum load. Once under way, dynamic lift can be used to offset loss of superheat. The degree of superheat may change rapidly. It is increased by radiation reflected from sandy soil, water surfaces, and the upper surfaces of fogs and clouds; it is decreased by passage through

cloud shadows and proximity to cold surfaces. The average intensity of negative superheat is less than that of positive superheat. Negative superheat is ordinarily greatest after midnight or when the ship ascends rapidly through an inversion.

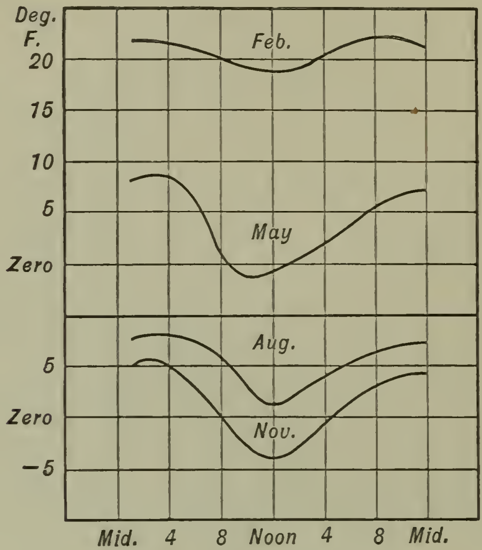

Figure 72. Hangar Superheat

Vertical scale gives temperature difference between air in hangar and outside air. To convert ° F. to ° C., subtract 32 and multiply by 5/9.

In Figure 72 is shown the average diurnal range of hangar superheat at Lakehurst for the most representative months. The values include all cases regardless of weather. Hangar superheat is influenced greatly by type of hangar construction, and by local factors. Artificial heating does not enter into the values in Figure 72 during the summer months, and only to a very limited extent in the winter months. Hangar superheat is used to obtain increased lift in take-off. The take-off must follow undocking without delay to avoid loss of superheat. The ship's superheat obtained in this way sometimes amounts to 10° or 15° F. (6° to 8° C.).

Other weather elements. Other chapters in this volume discuss the several weather elements, atmospheric pressure, humidity, fog, clouds, rain, snow, sleet, ice, and others in their general relation to aeronautical meteorology. In many respects, the discussion applying to heavier-than-air craft applies also to lighter-than-air craft. On the whole, airships are more concerned with detailed data regarding these weather elements than are airplanes. The questions of frequency of precipitation, excessive rainfall and snowfall, their seasonal and diurnal distribution, average amounts, the average humidity, the usual variations in humidity, and numerous other subjects are more often required in connection with airships than with airplanes. Detailed information on these subjects is to be obtained from climatological records and publications. Some reference to their application will be found in manuals on airship operation.

Meteorological Surveys and Equipment for Airship Bases

Meteorological surveys. A detailed survey of the conditions of wind and weather before selection of a site for an airship base should ascertain that conditions are favorable for frequent docking and undocking in all seasons. The regional climatological facts which should be presented in the survey are frequency and distribution of low clouds and fog, rain, snow, sleet, thunderstorms, heavy wind squalls, and violent wind shifts. Monthly or seasonal distribution, and hourly distribution should both be given. The survey should show the average amount of precipitation; the frequency and seasonal distribution of excessive rain and snowfall; and the number of days with ground covered by snow. It should present temperature data giving the customary averages and the frequency of freezing weather and extreme diurnal changes. A study of local topography is often important in making use of climatological data, especially if the climatological stations are some distance from the site under considera-

tion. Topography is the cause of significant differences in weather within short distances. Such differences are likely to arise not only in the case of wind, but also in fog, cloudiness, precipitation, and thunderstorms. Localities especially favorable for thunderstorm development are to be avoided. In some hilly regions distances of a few miles show appreciable differences in the frequency of thunderstorms. Besides the study of topography, it is sometimes necessary to investigate instrumental exposures and observational methods to arrive at the correct interpretation of climatological data.

Wind. Unless the site is in a region of unusually low wind velocity, a detailed study of the wind conditions on the exact site is very necessary. The conditions which are most important are: (1) absence of excessive air turbulence and local air disturbance; (2) regular and frequent periods of low wind velocity; and (3) steadiness in wind direction. Turbulence studies are made by artificial smoke clouds released in the wind stream. The study properly includes observations of wind from every quadrant covering a large range of velocities. For freedom from turbulence, a broad plain without trees or other obstructions is best, preferably adjacent to a body of water over which wind turbulence is likely to be at a minimum. But such a site usually has the disadvantages of relatively high average wind velocity and much variation in wind direction. While not without objections, it is usually agreed that a very broad, gentle valley lying approximately at right angles to the prevailing wind constitutes the best site in most regions. The surrounding country should be free from high ridges and peaks. It is desirable that the site be a few miles inland away from sea breeze effects. The valley directs the wind flow and increases constancy in direction. It also reduces the velocity of cross-valley winds without greatly increasing the turbulence of light to moderate winds in which airships are usually docked and undocked. The wind velocity is further reduced by the temperature inversion which forms

rapidly in the valley at night. Such a site usually provides the nearest approach to a docking and undocking period every day. The temperature inversion in a valley is not objectionable if not too extreme. In connection with the survey of local turbulence over the site, it is desirable to determine whether there are differences in terrain or topography which produce unusual vertical currents at a place which the ship will cross in making a low approach for a landing. Such currents, while not serious, are often troublesome in landing. Proper survey usually points out means for avoiding them.

Prevailing wind. To decide upon hangar orientation, a Table giving frequency of occurrence of winds from different directions is necessary. This information is most useful when classified according to velocities. It may give, for example, the number of hours, classed by months or seasons, during which the wind blew from north with velocity 5 m.p.h. (2 m.p.s.) or less; the number of hours from northeast with velocities 5 m.p.h. (2 m.p.s.) or less, and so on for all directions. Similarly, data for every direction with the velocities between 5 and 10 miles per hour (2 and 4 m.p.s.); also with velocities 10 to 15 miles per hour (4 to 7 m.p.s.); 15 to 20 miles per hour (7 to 9 m.p.s.); 20 to 30 miles per hour (9 to 13 m.p.s.); and above 30 miles per hour (13 m.p.s.). This permits orientation of hangar with respect to the wind direction which occurs most frequently when velocities are within the docking limits. The data are used also in location of masts and buildings which obstruct landing approaches. The wind data can be made to apply still more directly to the problem of orientation if they show the number of days in each month or season when each of the above wind classes has existed for a period of an hour or more. This shows the orientation which will give the greatest number of favorable docking days and avoids incorrect interpretation of data for a site on which there are decided seasonal tendencies in the foregoing wind classes. The effect

of seasonal tendencies is to give a large number of favorable days in some seasons, and relatively few in others. Data of prevailing directions alone are very unsatisfactory in airship base surveys. In most localities, the prevailing direction occurs less than 50% of the time. The survey should ascertain that the prevailing direction is the *usual* wind direction, not simply the direction which occurs more frequently than any other single direction. Here again, the comments previously made relative to average values are applicable. It is especially important to understand how the wind data were derived and how they may be correctly used.

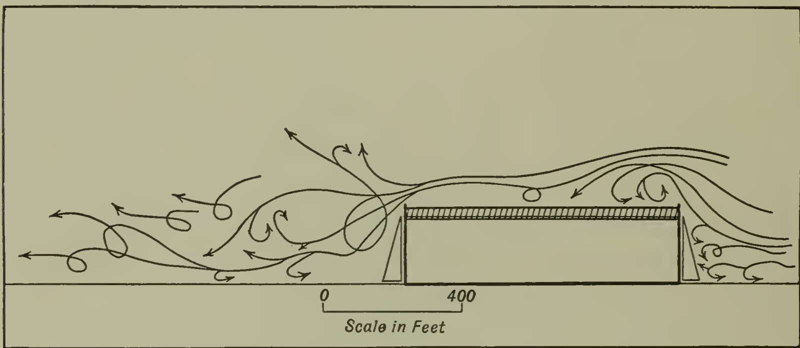

Figure 73. Eddies in Wind-Flow Over Hangar

View from side with wind direction parallel to longitudinal axis of hangar. To convert feet to meters, multiply by 0.3.

Hangar winds. Observations of wind flow by use of smoke clouds are of assistance in determining turbulence around a hangar. Knowledge of the turbulence shows the conditions which should be avoided in docking and undocking. Figure 73 shows the principal streams of wind flow over the hangar at Lakehurst when the wind is parallel to the hangar. The zone to leeward of the hangar in which there are strong descending currents is a critical place during docking and undocking through the leeward door. Winds not parallel to the hangar in direction are attended by different forms of turbulence. Recently designed hangars have streamlined

shapes and circular doors which roll back against the sides of the hangar to reduce turbulence to a minimum. Wind screens of various types designed to smooth out wind flow, have not attained practical success either in wind tunnel models or in full-scale tests. Related to the subject of turbulence in winds around hangars are the winds induced by the hangar. The heating of the hangar by the sun on a clear day often results in an appreciable surface wind circulation toward the hangar, sometimes enough to reverse the natural wind in light gradients. The heated air confined in the hangar has been known to set up a light wind lasting for several minutes after opening the hangar doors and allowing the warm air to escape upward.

Meteorological equipment. The meteorological observatory is usually isolated so that it may obtain observations of true open air conditions. Many of the standard instruments are described in Chapter 2. The observatory equipment includes barometers, barograph, thermometers, thermograph, psychrometer, hygrograph, anemometers with recorders giving total or average wind movement, anemobiagraph giving record of wind direction and gustiness, and theodolite with balloons and accessories for upper wind observations. Besides this standard equipment, it is desirable to have distant recording thermographs or tele-thermometers installed on a mast or tower for measuring temperature inversions. The inversion data make it possible to compute the static condition of the ship which is best suited to the existing temperature distribution during landing and take-off. Other equipment includes visual indicating anemometers or gust indicators installed at points around the edge of the field for use in carefully observing wind conditions during docking operations. The indicators exhibit signal lights which are visible from any point on the landing area. The observatory is usually equipped for upper air soundings by meteorograph to obtain data for forecasting. Static recorders or ceraunographs are sometimes

installed. Inasmuch as the preparation of weather maps is an important part of the daily routine, the observatory has telegraph or radio facilities through which it receives the general weather reports required for the map. In the United States, these general synoptic weather reports are received twice daily, and the maps drawn therefrom are the general weather map, the upper wind map, the pressure change and cloud charts, and occasionally charts of pressure and temperature aloft.

Forecasting Weather for Airships

In preparing weather forecasts for airship operation, the general principles of weather forecasting discussed in Chapter 10 are supplemented by greater attention to local details of weather than is the common practice. The forecasts aim to describe the coming weather in as much detail and for as long a period as possible. They are often required to include information of humidity, estimated amounts of precipitation, maximum and minimum temperatures and probable surface wind direction and velocity during certain hours. Forecasts of humidity, for example, are important in plans for handling gas cells. Forecasts of amount of snow or rain are important because the weight of the precipitation changes the static condition of the ship. This is especially true during landing and take-off when the ship is stationary and may collect several hundred pounds of rain or snow in a few minutes. The general aspects of airship weather forecasting in which it differs somewhat from forecasting for other purposes, are illustrated briefly in the following paragraphs. Examples are given to show typical aspects of the subject. Full discussion properly belongs to the treatise on weather forecasting and to the airship manual.

Weather maps. In flight a large airship prepares weather maps and forecasts much the same as a weather forecasting station on the ground. The synoptic reports for drawing

the maps are obtained by interception of radio weather broadcasts. In the United States, the following maps are customarily drawn aboard a large airship: the general weather map of the United States and Canada, the upper air map, and the pressure change and cloud charts. Attention is given in particular to analysis of the map and location of air-mass boundaries. The object is to determine as minutely as possible the structure of the fronts and the causes and characteristics of areas of cloudiness and precipitation. When avail-

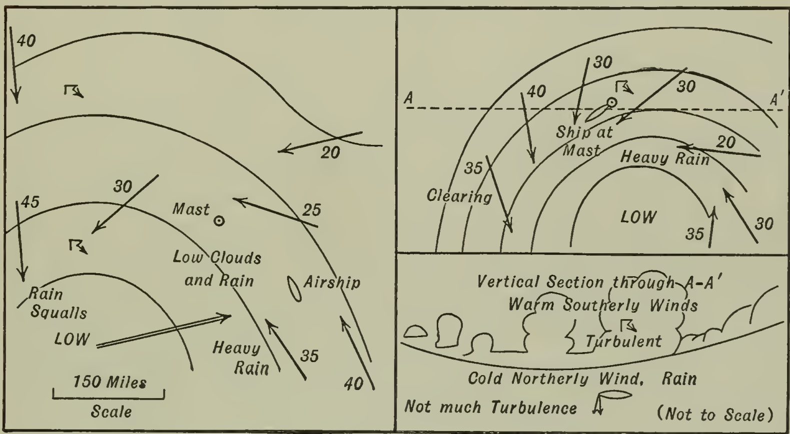

Figure 74. Showing Passage of Thunderstorm Above Warm-Front Surface

Arrows show wind directions; figures near them give velocities in m.p.h. To convert miles to kilometers, multiply by 1.6; m.p.h. to m.p.s., multiply by 0.45.

able, upper air soundings of temperature and humidity are plotted and used as an aid in frontal analysis. The cloud chart shows types of clouds and directions of movement and is useful in filling gaps in the upper air reports and revealing details of structure which would not otherwise be apparent. The conclusions drawn from such an analysis form the basis for forecasts of the development and movement of storm systems which may influence the navigating plans of the airship. The cases illustrated in Figures 74 and 75 are maneuvers which have been used successfully in airship operations.

Storm structure and airship navigation. Figure 74 illustrates how analysis of storm structure may be used in airship navigation. A storm is developing over the ocean south of a large area of high pressure. The arrows and numerals in the figure represent the wind at flying altitudes. The ship is heading for a point about 300 miles south-southeast of its position as shown in the left portion of Figure 74. The storm is increasing in intensity. The northerly winds in its rear are strong. There are indications of a severe squall line. The overcast condition of the sky makes it impossible to see the squall clouds and therefore difficult to select a navigable portion through which to pass. The southerly extent of the storm is uncertain, but apparently it is sufficient to prevent detour southward around the front. Land station reports north of the storm center show thunderstorms with heavy rain.

A study of the weather maps and upper air reports indicates that the thunderstorms are occurring above a warm front and are the result of instability due to condensation in an air mass which has a temperature lapse rate less than the saturated adiabatic. This conclusion indicates that the thunderstorm turbulence is confined largely to the warm southerly air above the frontal surface. An airship mooring mast is available at a point somewhat north of the probable "track" of the storm center and about 150 miles (250 km.) northwest of the ship's present position. By going to this mast and mooring until the storm center has passed, the ship avoids flying through the low clouds and wind shift extending southward from the storm center. It also avoids flying through the thunderstorm conditions north of the center. At the mast it rides through fresh to strong northeast and north winds without an abrupt wind shift and with little turbulence from vertical currents. It encounters heavy rain, but there is no course by which the rain can be avoided. The situation about 6 hours after the first map is shown in the right portion of the figure. The ship is moored and the thunderstorm condi-

tions are passing overhead. After the storm center has passed and the wind has backed to north-northwest, the ship takes off for its original destination with strong following winds. The time of arrival at destination by this maneuver is only a few hours later than if the ship had continued its course direct from the position first shown. In the latter case, the head winds of 30 to 40 miles per hour (13 to 18 m.p.s.) velocity would have greatly reduced its speed. These strong southeast

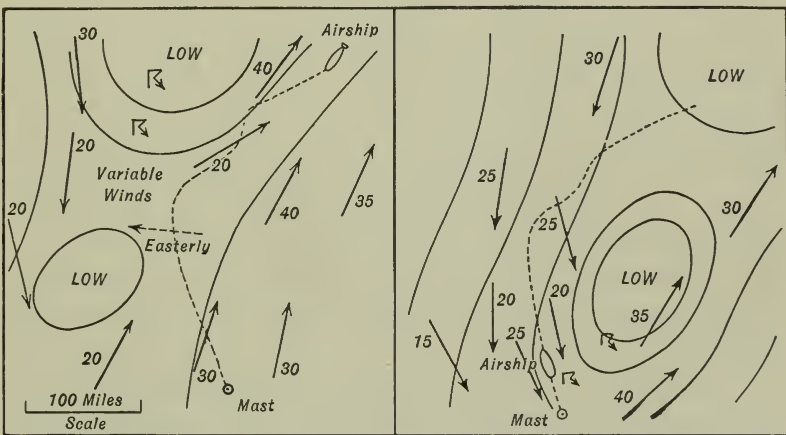

Figure 75. Detouring a Secondary
Arrows show wind directions; figures near them give velocities in m.p.h. To convert miles to kilometers, multiply by 1.6; m.p.h. to m.p.s., multiply by 0.45.

winds and the light to moderate east and northeast winds farther north aid the ship in reaching the mast and mooring before the surface winds become too strong. The northerly winds following the storm give it a ground speed two or three times as great as its speed on the direct course and thus make up in part for the delay while moored to the mast. It is plain that the success of this and similar maneuvers, depends upon the weather map analysis and the forecast.

Secondary Low. In Figure 75 is shown another meteorological distribution in which a ship's course is modified to make the best of wind and weather. A Low with a trough

and secondary extending south-southwest is moving eastward with a speed of translation of about 25 miles per hour (11 m.p.s.). The winds at flying levels are as indicated by the arrows. Thunderstorms are occurring along the trough of the primary Low. Information obtained from the temperature distribution, the pressure-change chart and the wind-aloft chart indicates that the secondary will intensify and develop thunderstorms south of its center. The destination of the airship is the mooring mast 300 miles (500 km.) south-southwest of the ship's position at the time of the weather map shown on the left of Figure 75. If the ship heads directly for the mast at a speed of 75 miles per hour (34 m.p.s.), it makes good about 40 miles per hour (18 m.p.s.) and at the end of 6 hours is still about 60 miles (100 km.) from the mast. About this time the ship must either go through the wind shift of the secondary which has now increased to a storm of considerable intensity, or must give way eastward in the attempt to find an opening in the line squall accompanying the wind shift.

If, instead of heading directly for the mast at the time of the map on the left in Figure 75, the ship heads southwest toward the southern end of the wind-shift line in the primary Low, it makes a ground speed of about 40 miles per hour (18 m.p.s.) for about 2 hours after which the speed increases to about 55 miles per hour (25 m.p.s.) as a result of the decreasing winds aloft. After the third hour, the ship is close to the wind shift. The warm sector of the Low eastward of the shift is generally clear and the clouds along the cold front are visible. If the clouds to the westward indicate that the front is still accompanied by thunderstorms, the ship turns southward along the line until the thunderstorm clouds are left behind and the quieter portions in the secluded front just north of the secondary are reached. Here the air is less turbulent and the ship passes southwestward through the variable or light easterly winds and gradually into the

strong northerly winds in the rear of the secondary. It then heads toward the mast. With the help of the strong northerly winds it makes a ground speed of 90 miles per hour (40 m.p.s.), and completes the remaining distance in 2 to 3 hours. The total time required to travel the distance of about 400 miles (650 km.) over the indirect route is approximately 6 hours. This is less time for the passage than if the ship's course had been laid directly for the mast. Moreover, the ship has avoided the severe portion of the wind shift and has gained the northerly winds behind the shift. It is therefore in position to moor at the first opportunity after the winds at the mast steady on north or northwest. On the indirect course the ship encounters less rain than on the direct course which lies through the region of heavy showers.

Gales. There are many cases in which it is advantageous to take a circuitous course to avoid strong head winds. To plan such a course intelligently, rather definite forecasts are necessary giving the location and extent of the zone of strong winds. The gales in a storm rarely extend more than a few hundred miles in the direction at right angles to the wind. The shortest way to get out of the gales lies directly across wind. This course is not usually the most economical. It is not used unless the gales are attended by very bad weather, making it desirable to get into lighter winds as quickly as possible. The best course usually lies between the extremes of heading directly across and directly into the gale. It depends upon wind distribution and rate of movement of the storm as well as the position of the ship with relation to these two characteristics. The correct solution of the problem in each case is based upon a foreknowledge of the movement and development of the storm in the immediate future. Often an indirect route can be selected which results in completion of the passage in shorter time than the direct route in addition to avoiding the most unfavorable weather.

Storms which develop rapidly. The bad weather conditions which develop very rapidly and with little indication require special attention in airship weather forecasts. One of these conditions is the rapid spread of warm-front rain from the west Gulf states northeastward to the Atlantic coast. In extreme cases, very bad flying conditions with low clouds, fog, rain, and occasionally sleet overspread several states within 12 hours. In some of these cases, only clear weather would have been expected from a casual glance at the weather map. Examples of such conditions are contained in the weather maps for January 10 to 11, 1930, and October 23 to 24, 1925. Closely related to this kind of frontal formation are the secondaries which form in the Gulf of Mexico or pass across it outside the field of observation, later appearing in the east Gulf or along the Atlantic coast and bringing thick weather and sometimes gales. Other formations which are closely watched in airship operations are V-shaped depressions in which temperature and wind contrasts show the likely development of line squalls; also irregularities in isobars and winds. These are the first indications of the formation of cloud areas and secondaries which may enter into navigating plans. The principles illustrated by these four examples are some of the many which can be presented only in longer discussions of forecasting.[4]

Cloud prognostics. It is not unusual for the appearance of the clouds to give the first definite indication of coming bad weather. This is the case especially when the unfavorable weather is local or when it is a new development which did not appear on the preceding weather map. Many of the cloud prognostics of long standing are well known. They can be studied in more detail in other books on weather.[5]

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[4] The references to irregularities in the isobars and local thunderstorm indications in this chapter were included in the first edition of "Aeronautical Meteorology," pp. 108 to 109 in paragraphs prepared by Lieut. J. B. Anderson, U.S.N., then attached to the airship U.S.S. *Shenandoah*. The present references are based on Lieut. Anderson's paragraphs.

[5] W. J. Humphreys. "Weather Proverbs and Paradoxes." C. F. Brooks. "Why the Weather." A. W. Clayden, "Cloud Studies."

An indication which is useful, especially when operating at sea where weather reports are scattered, is the characteristic sequence of clouds in advance of a storm. When well-defined cirrus clouds (mares' tails) thicken into cirro-stratus and the clouds then gradually lower into watery alto-stratus, they are usually the precursor of a storm. In 70% to 80% of the cases, the storm arrives within 12 to 24 hours after the appearance of the cirrus and cirro-stratus. A well-formed mackerel sky usually is the result of the wind currents in the front portion of a Low. These cloud forms are evidence of frontal formations. They are useful in supplementing the analysis of the weather map. Cloud characteristics are the best and often the only indication of the exact location of severe squalls and thunderstorms. Every towering cumulus cloud marks the upper portion of an ascending current. When a cumulus develops into a squall cloud, it usually takes on a ragged and ugly appearance, often with streamers of rain below it. Over bodies of water the "cat's paws" on the water give some indication to aircraft of the places where the descending currents and turbulence near the surface are most violent. The characteristic false cirrus clouds spread out into mushroom shape, or resembling an anvil when viewed from the side, are well known as the mark of a severe thunderstorm. On a hot summer afternoon when the surface air is thick with haze, the whitish top of the anvil of false cirrus just above the haze horizon with a bluish darkening of the air below it, may be the first indication of an approaching thunderstorm. An earlier indication of summer thunderstorms is sometimes given by the appearance of turreted alto-cumulus clouds. When these towering clouds appear in the morning in large numbers, they show instability and moisture at high altitudes—conditions which favor thunderstorm development in the afternoon.

A particularly dangerous source of thunderstorm formation is that in which the storms are caused by overrunning

of cold air when the sky is overcast. Thunderstorms from this cause may appear without warning over a large area almost simultaneously. Such a condition existed over eastern Ohio during the night of September 2 to 3, 1925. Because of the impossibility of seeing the squall clouds, it is extremely hazardous for aircraft to remain in the air under this condition at night or when the sky is overcast. As another example of a weather distribution which gave extremely rough flying conditions over the New York to Cleveland airway due to instability attending heavy showers, reference may be made to the weather map for October 12, 1927. Instrumental indicators based upon electrostatic or electromagnetic ("static") principles for showing the location of thunderstorms have not yet been perfected. Such instruments would be particularly valuable at night or in an overcast sky. Advices as to the proper direction to fly to detour line squalls depend upon the weather map as well as local appearance of the clouds. Usually when the Low center lies to the north, the line squall becomes less intense farther south. In this case, the best course is southward or southeastward along the eastern side of the line squall until a clear space is found leading to the northwest winds in the rear of the wind shift. Sometimes, however, the weather maps show that the outburst of cold air is more abrupt and intense to southward and that milder conditions for passage through the front are to be found to the north.[6]

Use of local data in forecasting. One of the functions of the aerological observatory is to record data of local conditions, and compile and present them in a form suitable for use in preparing local forecasts. Continuous records for a year or more are needed for this purpose. It is advantageous for the detailed survey of the airship base site to include such

[6] Thunderstorm forecasts based on thermodynamic analysis of local air masses are possible in some cases through study of tephigrams of upper air data. See C. M. Alvord and R. H. Smith, "The Tephigram, Its Theory and Practical Use in Weather Forecasting," *Monthly Weather Review*, Vol. 57, No. 9, September, 1929.

data. These local forecasts are very useful in undocking and docking schedules. It is usually most convenient to make use of the local data in graphical form. Some typical uses are described below.

Local wind forecasts. It is of much assistance in forecasting the decrease of wind about sunset if the daily wind records for the locality are classified according to wind gradient and condition of the sky. The resulting types can be represented graphically. Wind direction may also be introduced as an argument in the graphs to provide greater accuracy. The probable wind decrease for the coming evening is obtained by reference to the graph corresponding to conditions on the current day. Use of the values of wind aloft at 1,500 to 3,000 feet (450 to 900 m.) is usually a satisfactory substitute for wind gradient. Consideration of the graphs together with the prospective changes in general wind gradient during the night will show whether the wind is likely to remain at the decreased velocity all night, or is a sunset lull which will be followed by an increase during the night. The thermograph trace in the evening gives evidence of the formation of an inversion and therefore indirectly indicates the wind trend during the next hour or two. If the trace shows rapidly falling temperature, the surface wind velocity usually continues to decrease. If the temperature remains steady, or is rising, the velocity decrease is small or only temporary. As the wind decreases at sunset the wind direction often shifts under the influence of a different local pressure gradient at the surface. This forms cross currents one above the other at low altitudes which influence landing approaches and docking. They cause changes in dynamic as well as static lift. Forecasts of such conditions make it possible for the airship navigator to allow for them. Light winds at night are often modified in direction and velocity by passage of cloud layers which have developed circulations of their own. If the clouds pass during the night, they are usually attended by increased

wind velocity, at least for a time. If they occur during the day, the velocity is usually decreased, except when the clouds have reached squall proportions.

Forecasts of wind at definite hours during the day are facilitated by diagrams similar to those just discussed. Good results are obtained in forecasting maximum surface winds during the daylight hours through use of a factor applied to the wind at 1,500 to 3,000 feet (450 to 900 m.) altitude shown by pilot balloon soundings just after daybreak. Different factors are required for different conditions of sky and wind direction, and different seasons. One set of factors may be applied to determine the probable average hourly wind and another to determine the average gustiness. The accuracy of local forecasts prepared in this manner is well within practical requirements in most cases. Obviously, if the general wind gradient is changing rapidly, allowance must be made for the change either by estimation, or by subsequent pilot balloon soundings and new computations. On clear days, the surface wind in the afternoon usually reaches a velocity about half that of the early morning wind at 1,500 to 3,000 feet (450 to 900 m.). On cloudy or hazy days the ratio is much less. The factors to be used vary considerably with topography. Figure 26, Chapter 4, expresses this relation in an average form for two localities, including all types of days. The gust and squall characteristics mentioned in previous paragraphs are often of use in forecasting.

Temperature forecasts. Forecasts of maximum and minimum temperatures may be made by combining the changes expected from translation of air masses with the usual diurnal change for the locality under the current conditions of sky. The change due to air mass movement is determined from study of winds on the weather map. Allowance is made for probable diurnal modification during this movement. The amount of local diurnal change is determined from the records for the locality. There is a relation between tempera-

tures aloft and maximum surface temperatures which may be used if upper air soundings of temperature are available. The maximum temperature on the ground usually does not appreciably exceed the potential temperature of the air at the top of the early morning surface inversion. In some places, formulas have been derived for computing minimum temperatures based partly on dew-point. These formulas are not in general use. Forecasts of minimum temperature have been, in turn, used in connection with observations of dew-point to determine the approximate hour of formation of radiation fog on the landing field as a factor in landing plans. The use of graphs based on local records has been extended in a few instances to forecasting inversion conditions for airship take-off and landing. The coordinates of these graphs may take into account the condition of sky, the wind, the absolute temperature and the period of darkness. Fairly satisfactory results are obtained by using only the first two factors as arguments. Similar graphs can be prepared for expressing the behavior of other local weather elements such as the time of arrival of sea breeze, the probability of formation of fog under certain conditions of humidity and wind, and the time required for radiation fog to disappear under certain conditions of wind and sky. Like the graphs mentioned previously, they are usually limited to local application. They are often the only means by which definite advices of the local conditions which influence airship handling may be presented.

CHAPTER 12

NORTH ATLANTIC AND ARCTIC METEOROLOGY

As aircraft are improved in design and construction, as their speed and cruising radius are increased, and as radio and other navigational aids are perfected, flying over the oceans will become increasingly important. It is here, indeed that in many respects air travel shows up to best advantage in comparison with other available means of transportation. On land it is possible to travel by train or bus at speeds approximately double those attained by the fastest ships. At sea, moreover, all distances are great and therefore travel by air, since there are no time-wasting stops en route, reaches its highest possible efficiency.[1]

Unfortunately, meteorological conditions are notoriously bad over much of the ocean surface, particularly over those portions where travel is likely to be greatest, namely, in the temperate zones. However, full knowledge of conditions as they exist usually results in their ultimate conquest. Let us see with what the pilot of the future and his aircraft are to contend if they are to win in this battle.

Although flights will eventually be made in greater or less number over *all* the oceans, chief interest in this country is centered at present in transatlantic and transarctic flying. Most attention, therefore, will be given to the conditions in these two regions, particularly in the North Atlantic, but first, reference is made to Figures 76 and 77, which show the prevailing surface winds on all the oceans between latitudes 65° N and 60° S, for the summer and winter seasons respectively. The steadiness of the trade winds is in marked

[1] The possible future development of floating airports will change this to some extent, but even then the distances will be much greater than those on land.

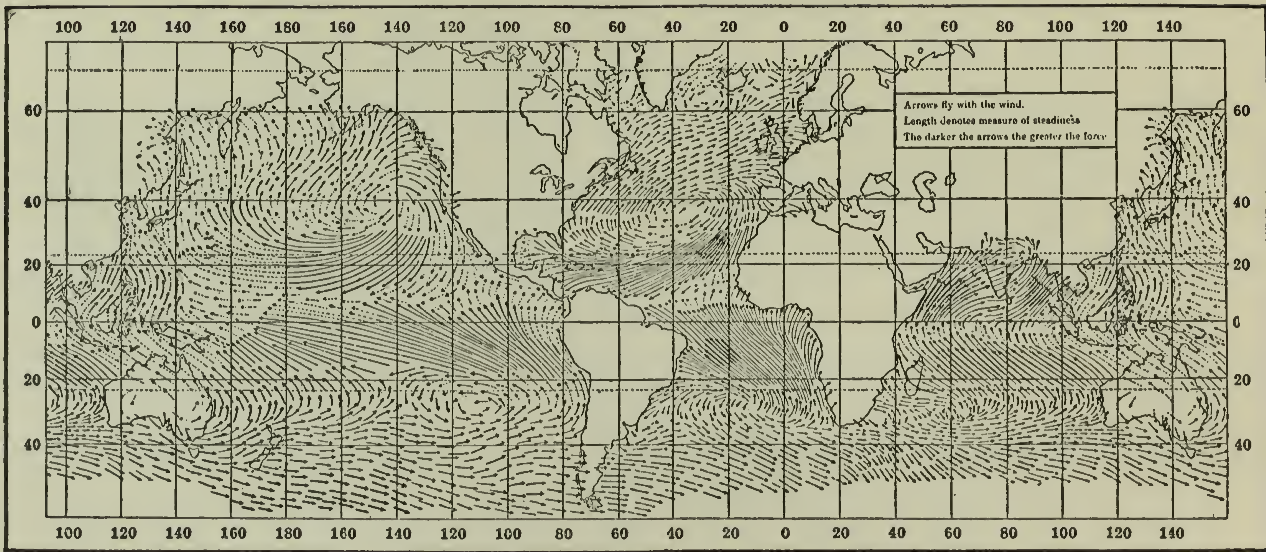

Figure 76. Ocean Winds, July and August

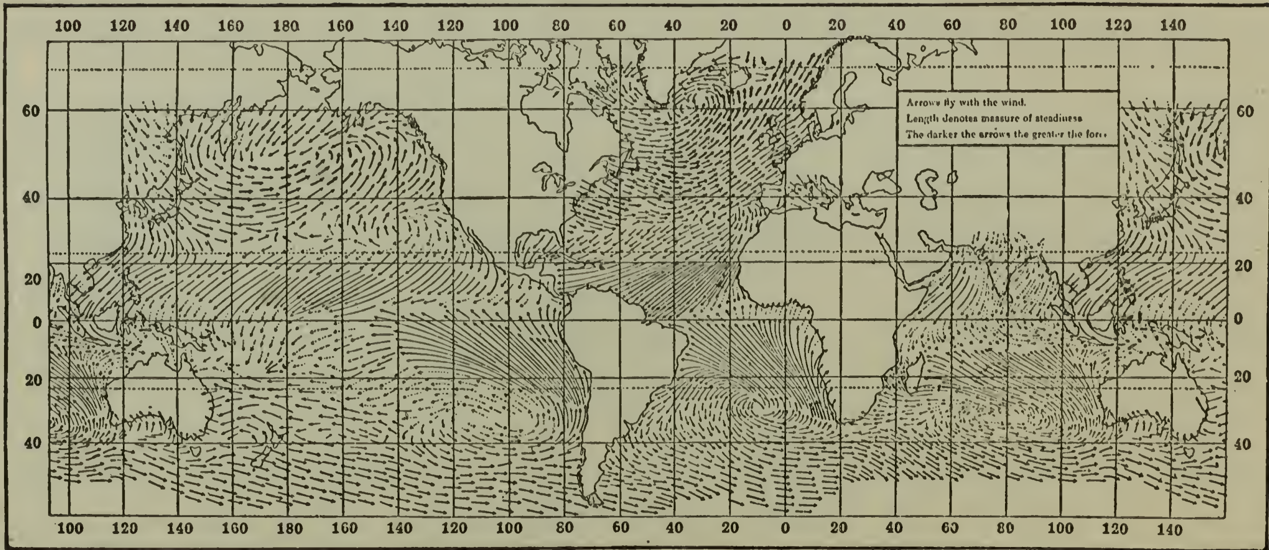

Figure 77. Ocean Winds, January and February

contrast to the variability of the prevailing westerlies in the temperate zones. (See discussion of the prevailing westerlies in Chapter 1.) Very useful and informative "Pilot Charts" are issued by the Hydrographic Office of the U. S. Navy for all the oceans except the Arctic and Antarctic. Those for the North Atlantic, North Pacific, Central American waters and Indian Ocean are published monthly and those for the South Atlantic and South Pacific four times a year, each covering a season. The data for these charts are furnished by the U. S. Weather Bureau, as are also those for a series of "Pilot Charts of the Upper Air" for the North Atlantic and North Pacific oceans. The publication of these upper air charts was begun in 1927. They contain wind frequencies for various heights at coastal and a few island stations. As time goes on, it is expected that upper air data will be secured above the oceans themselves, and the charts will increase in value accordingly. Copies of the charts above referred to may be obtained from the U. S. Hydrographic Office, Navy Department.

Flying over the North Atlantic

Possible routes. The shortest route from the United States to Europe is that to Ireland by way of Newfoundland and it is in this part of the Atlantic that the worst weather prevails. A somewhat longer route, but with better weather conditions part of the way is from Newfoundland to the Azores, thence to Portugal. Undoubtedly, the best one from the meteorological viewpoint is that by way of Bermuda and the Azores or still farther south, but this route is much longer than either of the other two. Finally, a route that has received some consideration, and in fact was followed in the "Round the World Flight" of the Army Air Service, is that between Labrador and Scotland via southern Greenland and Iceland. This has the advantage of comparatively short hops but is considerably longer than the direct one from Newfoundland

to Ireland and has the added disadvantages of lower temperatures, absence of weather reports and remoteness from steamship routes.

The routes that have received most consideration are those from Newfoundland direct to Ireland and from Newfoundland to Portugal by way of the Azores. Being shortest, they are most attractive commercially. Moreover, they parallel the chief lanes of steamship travel and therefore have available a more complete network of weather reports than do the others. It is believed well worth while, therefore, to consider in some detail the meteorological conditions along the routes where thus far most of the attempts to fly across the Atlantic have been made.[2]

Surface conditions; temperature. Little attention would be paid to temperature were it not for its association with the occurrence of snow and ice, the formation of which on the planes is probably responsible for the failure of several of the attempted flights. In Table 18 are given average monthly and annual values of temperature at four selected places.

Annual and diurnal ranges as well as those due to abrupt changes in weather, are greatest in Newfoundland and least in the Azores. Minimum temperatures as low as −25° C. (−13° F.) have been observed at St. Johns and as low as −5° C. (23°F.) at Valentia. Freezing temperatures have never been reported in the Azores or at Lisbon. Extreme maxima do not differ greatly at the four places, Lisbon showing the highest, 35° C. (95°F.), and Valentia the lowest, 27° C. (81° F.).

Over the ocean, the horizontal temperature gradient is fairly steep in winter from Newfoundland to longitude 40° W

[2] For more complete discussions reference is made to the following: A Baldit, "Les Routes Aériennes de l'Atlantique Aperçu Météorologique," Gauthier-Villars et Cie., Paris, 1928, Ph. Wehrle, et A. Viaut, "Les Traversées et Tentatives de Traversées Aériennes de l'Atlantique Nord en 1927 Au point de vue Météorologique." Office Météorologique, Paris, 1928. G. Voitoux, "La Navigation Aérienne Transatlantique," Société d'Éditions Géographiques Maritimes et Coloniales, Paris, 1930. W. R. Gregg, "Trans-Atlantic Flight from the Meteorologist's Point of View," *Monthly Weather Review,* Vol. 47, pp. 65-75, February, 1919.

along both routes, and practically zero from that longitude to Ireland and Portugal. During the summer there is a slight rise from Newfoundland to longitude 45° W over the Azores route; along the remainder of this course and along the entire course from Newfoundland to Ireland there is practically no change.

Table 18. Mean Monthly and Annual Temperatures, ° C., and ° F., at St. Johns, Newfoundland; Valentia, Ireland; the Azores; and Lisbon, Portugal

	St. Johns		Valentia		Azores		Lisbon	
	° C.	° F.	° C.	° F.	° C.	° F.	° C.	° F.
January	−5	23	7	45	14	57	10	50
February	−5	23	7	45	14	57	11	52
March	−2	28	7	45	14	57	12	54
April	2	36	9	48	16	61	14	57
May	6	43	11	52	17	63	16	61
June	11	52	14	57	19	66	19	66
July	15	59	15	59	21	70	21	70
August	16	61	15	59	22	72	21	70
September	12	54	14	57	21	70	20	68
October	7	45	11	52	19	66	16	61
November	3	37	9	48	17	63	13	55
December	−2	28	7	45	15	59	10	50
Annual	5	41	10	50	18	64	15	59

Relative humidity. Comparatively little has been done in a critical way in the study of humidity conditions over the oceans. Among the most interesting observations are those on the British steamship *Scotia* and on the U. S. Coast Guard Cutter *Seneca*. These observations were made in the late spring and early summer months and showed in practically all cases a relative humidity above 80%. A large number of observations in December, as computed by the marine section of the Weather Bureau, gave an average value of 86%. There seems to be little, if any, variation with the seasons, but there is a small variation with latitude, values at latitude 60° N averaging about 90%, as against 85% at latitudes 40° to 50° N.

Cloudiness. The average cloudiness along the northern route is about 70% throughout the year. This statement is somewhat misleading, so far as aviation is concerned, inasmuch as fogs are included with clouds in arriving at this result and, as will be shown later, these fogs extend to low altitudes only. The pilot would often have a clear sky above him, whereas at the earth's surface 100% cloudiness would be recorded. It is probable that in summer the average cloudiness above the fog level is about 50% to 60%. Between Newfoundland and the Azores it varies from 65% in winter to 55% in summer, and between the Azores and Portugal, from 55% to 45%.

Precipitation. Very little is known as to the amount of precipitation over the North Atlantic Ocean. Data are available, however, for the adjoining coasts and these indicate an annual amount of about 140 centimeters in Newfoundland; 100 on the west coast of Ireland and in the Azores; and about 70 in southern Portugal (or 55, 39 and 28 inches, respectively). According to Supan, the average is about 200 centimeters (79 in.) over the greater portion of the Newfoundland-Ireland route, and over part of the region between Newfoundland and the Azores; from the latter to Portugal the mean value is probably about 100 centimeters (39 in.). Precipitation normally occurs on about 160 days in Newfoundland; 200 in Ireland; 170 at the Azores; and 100 in Portugal. Over the ocean it probably occurs on about 200 to 250 days along the northern route and on about 150 to 200 days along the southern route. In all regions precipitation is greatest in winter and least in summer.

Fog. One of the most serious obstacles to transatlantic flight appears to be the large percentage of days on which fog occurs, particularly near the American coast. In the regions southeast and east of Newfoundland this amounts to about 60% in summer and about 20% to 35% in winter; the fre-

quency in the latter season being greatest to the southeast. Near the Irish coast, it varies from about 10% in summer to 5% in winter. Fogs rarely occur near the Azores or between them and Portugal. A surprising feature of this part of the Atlantic is a calm-weather fog of small vertical extent in which the sea is slightly warmer than the air. In discussing this phenomenon, Taylor [3] concludes "either that when a fog blows over warmer water there is no appreciable tendency to dissipate it or that, under certain circumstances, warm water under cold air tends to produce a fog in some other way than that with which we are familiar and that this effect balances the tendency of warm water to dissipate a fog produced by cooling." Probably such fogs are of a temporary nature, having already been formed under the usual conditions, but later blown over water with a higher temperature than their own. They occur only during calm weather and quickly disperse as soon as a breeze sets in.

Pressure. Pressure distribution over the North Atlantic may be briefly described as consisting essentially of a belt of high pressure, known as the "Horse Latitudes" at about latitudes 30° to 35° N, with a semi-permanent High near the Azores; and a belt of low pressure at about latitude 60° N with lowest values in the vicinity of Iceland. Because of the relative warmth of the ocean and the adjacent continental areas during the different seasons, the Azores High is best developed in summer and the Iceland Low in winter. The seasonal difference is greatest in the case of the Iceland Low, the final result being that the northward pressure gradient is strong in winter, but relatively weak in summer. The isobars, in general, run more or less parallel to the lines of latitude from Newfoundland to about longitude 20° W at all seasons. Farther east along the Ireland route they continue eastward in summer, but turn to east-northeast and northeast in winter,

[3] G. I. Taylor, "Report on Meteorological Observations: Part of a Report on the Work carried out by the S. S. *Scotia*," London, Darling and Son, Ltd., 1913.

under the influence of the Iceland Low. From the Azores to Portugal they turn southward in summer around the Azores High, but are nearly west to east during the winter.

Winds. As a result of the pressure distribution, thus briefly outlined, winds in summer are from a west-southwesterly direction, with a mean velocity of 8 meters per second (18 m.p.h.) at all points along the northern route; in winter they are westerly, with a slight component from the north, mean velocity about 10 meters per second (22 m.p.h.) from Newfoundland to longitude 45° W. Farther east they have a strong south component, becoming southwesterly near the British Isles. The mean velocity along this section of the course is 10 to 15 meters per second (22 to 34 m.p.h.) being highest between longitudes 45° and 20° W. Over the southern course winds in summer are southwesterly, 8 meters per second (18 m.p.h.) to longitude 40° W; variable and light thence to the Azores; and northerly, 8 meters per second (18 m.p.h.) between the Azores and Portugal. In winter they are west-northwesterly, 10 meters per second (22 m.p.h.) to longitude 40° W; westerly, 10 to 12 meters per second (22 to 27 m.p.h.), thence to the Azores; and west-southwesterly, 10 meters per second (22 m.p.h.) between the Azores and Portugal. The percentage of winds from a westerly direction, that is, between north-northwest and south-southwest, varies along the northern route from about 85 in winter to 70 in summer; near the Azores, from 75 to 65; and from the Azores to Portugal, 40 to 30. In the last-named region winds from all directions are about equally frequent in winter, but in summer northerly winds predominate.

Gales. Practically all of the cyclonic disturbances that move across the United States, no matter what their place of origin, enter the North Atlantic Ocean slightly to the south of Newfoundland, moving thence east-northeastward toward the Iceland Low, and thus crossing the northern route roughly

between longitudes 30° and 40° W. These storms vary considerably in size, intensity, and rate of travel. In general, they are larger and travel more slowly over the ocean than over the continents. They are, moreover, more frequent, more intense, and faster moving in winter than in summer. In their movements across the Atlantic, the more intense cyclones are often accompanied by gales having a velocity of more than 20 meters per second (45 m.p.h.), the directions of these gales depending upon the part of the storm in which the observations are made. Thus considering a typical case, viz., a well-developed Low leaving New England and passing south and eventually east of Newfoundland, we should expect to have at the latter place gales successively from the east, northeast, north, northwest, and west. Along the Ireland route the percentage of days on which such gales occur varies in general from about 25 in winter to 5 in summer. In winter they are often accompanied by violent snow squalls. From Newfoundland to the Azores, the percentage frequency of gales is about 20 in winter and 3 in summer; from the Azores to Portugal, about 7 and 1, respectively.

Tropical cyclones. The chief features of tropical cyclones, or hurricanes, have been discussed in Chapter 9. As there stated, these storms average only about 6 a year and, on leaving tropical latitudes, assume the characteristics of the cyclonic storms of middle latitudes. So far as transatlantic flight along the two courses under consideration is concerned, the pilot need therefore feel no more anxiety from hurricanes than from the areas of low pressure that originate in different portions of this country and enter the Atlantic Ocean from the St. Lawrence valley.

Upper air conditions. On this subject there is but little information available, so far as actual observations are concerned. The following discussion is, therefore, based for the most part on numerous upper air observations that have been

made over the eastern portions of the United States and Canada and in different parts of Europe, and an effort is made to apply these results to the air over the ocean, bearing in mind the relative effects of land and water surfaces on the distribution of the meteorological elements above them.

Temperature. Individual observations over land surfaces show, in the lower layers of the atmosphere, large variations in temperature gradients, from a strongly inverted condition to nearly (sometimes slightly exceeding) the adiabatic rate. The diurnal phase, so characteristic of surface temperatures, disappears at a low altitude. At higher levels the phase remains nearly the same as at the surface, but the amplitude is very small, averaging about 1° C. (2° F.). The annual variation is also less in the upper air than at the surface, with the result that in winter there is on the average little change in temperature from the surface to a height of about 1 kilometer (3,300 ft.) above it, whereas in summer a decrease of about 6° C. (11° F.) occurs. In general, it may be said that the lower the surface temperatures, as compared with the seasonal normal, the smaller is the rate of decrease with altitude. In other words, during cold waves with clear skies and especially during the early morning hours, inversions almost invariably occur. During cloudy weather, that is, low clouds, temperatures generally decrease from the surface to the cloud layer and increase slightly for a short distance above it.

In the application of the foregoing statements to the air above the ocean, it is important to recognize certain fundamental differences between land and water surfaces in their absorption and radiation of temperature. Water surfaces reflect about 40% of the insolation that reaches them and absorb the remaining 60%. Much of the heat thus absorbed is, however, used in evaporating the water and some of the remainder is distributed both vertically and horizontally by the constant movement of the water and by the penetration of the light rays to lower levels, the result being that the surface, and

therefore the air in contact with it, maintains a relatively constant temperature. Land areas, on the other hand, reflect and transmit very little insolation and there is but little evaporation. The specific heat of land is low and, moreover, there is no movement, as in the case of water, whereby the heat received can be convectionally distributed either horizontally or vertically. Hence, land areas become strongly heated during insolation and similarly cooled in its absence.

The diurnal variation of temperature at the surface in any one locality at sea is seldom greater than 1° C. (2° F.). In general it is probable that the change is not much larger in the air above the ocean, except that, in the case of coastal waters, winds blowing offshore would bring their characteristic diurnal variations of temperature with them. As has already been stated, there is in winter considerable change in surface temperatures from Newfoundland eastward. This is due partly to the effect of the cold winds blowing off the American continent and partly to the difference in temperature of the Labrador Current and the Gulf Stream. In the upper air this difference largely disappears. Observations on the *Seneca* invariably showed a sharp inversion above the cold Labrador Current and the coastal waters, whereas a temperature decrease of 0.5° to 0.6° C. per 100 meters (3° to 4° F. per 1,000 ft.) was found above the Gulf Stream. Summarizing, then, we should expect to find at 1 kilometer (3,300 ft.) above the sea approximately the conditions as set forth in Table 19. The summer months include June, July, August, and September; the winter months, December, January, February, and March. Transitions from one group to the other during spring and autumn are gradual.

It must be distinctly understood that these figures are merely estimates; they are the nearest to actual conditions that we can get at the present time. They indicate that at an altitude of 1 kilometer (3,300 ft.) temperature changes along both routes would be less than at the surface, that rarely would

temperatures be much below freezing along any part of either route, and that in summer a trip would be attended by mild and comfortable temperatures throughout. The fogs off the coast of Newfoundland should cause no concern in this respect, for, as will shortly be shown, they are low-lying, and above them temperatures are higher than at the surface.

Table 19. Estimated Temperature Conditions, ° C., and ° F., at About 1 Kilometer (3,300 Ft.) Above Sea in Different Portions of the North Atlantic

	Near Newfoundland				Near Ireland				Between Azores and Portugal			
	Summer		Winter		Summer		Winter		Summer		Winter	
	°C.	°F.	°C.	°F.	°C.	°F.	°C.	°F.	°C.	°F.	°C.	°F.
Average	10	50	0	32	10	50	5	41	15	59	10	50
Highest	25	77	10	50	20	68	10	50	25	77	20	68
Lowest	5	41	−10	14	5	41	−5	23	10	50	5	41

Humidity. Over land areas, relative humidity generally decreases with altitude during clear weather or when only high clouds of the cirrus type are present. As a rule, it falls to about 50% at an altitude of 1 kilometer (3,300 ft.) but occasionally as low as 20%. When there are low clouds, the humidity remains high to the upper limits of the cloud layer and decreases rapidly above it. When all conditions of weather are considered, the average decrease with height is not large, amounting to only about 10% from the surface to 1 kilometer above it. It is greatest in winter and least in summer. At altitudes greater than 1 kilometer, the relative humidity remains practically constant. Above the ocean, due to the higher humidities at the surface, this decrease is probably larger, amounting on the average to 20% or 30%. The *Scotia* observations showed in some cases exceedingly low values at altitudes of less than a kilometer, even with dense fog at the surface. In general, it is probable that a pilot flying at an altitude of about 1 kilometer (3,300 ft.) would experience along the northern route humidities of 50% to 60% in clear

weather or when only high clouds are present and about 80% to 100% in weather with low-lying clouds. Along the southern route somewhat lower humidities than 50% would prevail during clear weather, but with overcast skies they would be about the same as along the northern route.

Height of fog. There is every reason to believe that in the great majority of cases fogs extend to a low altitude only, above the sea. This is clearly shown in the kite records obtained on the *Scotia* and on the *Seneca*. The top of the fog is very definite, and above it the relative humidity decreases rapidly. The temperature usually increases from the surface to the top of the fog and decreases above it. Out of nine kite records in fog obtained on the *Scotia*, only one showed fog extending to a height greater than 300 meters (1,000 ft.), the average being about 150 meters (500 ft.). Ten kite flights in fog were made from the deck of the *Seneca*, and the temperature gradients indicate that in only one did the fog extend to a height greater than 250 meters (800 ft.). In fact, there is nearly always a higher temperature at the top of the mast than on the ship's deck and, if this temperature increase continues to greater heights (and kite records show this to be true), a point must soon be reached at which fog is impossible. Additional testimony from local observers, in support of these conclusions, is contained in a report of the British civil aerial transport committee.

Winds. Observations with kites and balloons in the United States and in Europe have brought out the following facts with respect to average upper wind conditions. Velocities are slightly greater at all altitudes in America than in Europe, but aside from this difference the same general tendencies are shown in both countries, viz., a rapid increase, amounting to very nearly 100%, from the surface to about 500 meters (1,600 ft.) above it; practically constant velocity in summer and a small increase in winter from the 500 to the 1,000-meter

(1,600 to 3,300 ft.) levels above the surface; and a steady increase in both seasons, but greater in winter than in summer, from the 1,000-meter (3,300 ft.) level above the surface to greater altitudes. The mean seasonal difference is about 1 meter per second (2 m.p.h.) at the surface, and 2 to 4 meters per second (4 to 9 m.p.h.) at an altitude of 1 kilometer (3,300 ft.). Moreover, all observations show that the increase in wind velocity from the surface to 500 meters (1,600 ft.) is practically the same for all directions of wind, but that at higher levels winds from an easterly direction rapidly diminish in strength, whereas those from a westerly direction gradually increase. The easterly winds usually die out altogether before an altitude of 2,000 meters (6,600 ft.) is reached and at higher levels westerly winds prevail. The shifting from one type to the other is nearly always clockwise with surface winds from east to south and as a rule counterclockwise with surface northeast to north winds. The amount of the turning is directly related to the angle of deviation of the surface wind direction from that of the prevailing westerlies.

Winds, as is well known, tend to flow at right angles to the direction in which the pressure gradient acts, that is, parallel to the isobars. Owing, however, to friction and eddies, the direction of motion of the surface wind is nearly always inclined to the isobars. The amount of this inclination is greatest in anticyclonic and least in cyclonic systems, the average value on land surfaces being about 30°. Inasmuch as these disturbing influences largely disappear in the upper air, we should expect the winds invariably to veer with altitude. This veering with altitude is at times visible in the way in which the smoke from steamers spreads. That there are exceptions is due to the unequal vertical distribution of temperature that often obtains in adjacent localities, thus producing in the upper air isobaric systems decidedly different from those at the surface. Nevertheless, in general it is found that the winds at an altitude of 1 kilometer (3,300 ft.) follow

rather closely the direction of the surface isobars. This means that on the average they veer about 30° from those near the ground.

The case is somewhat different over the ocean. Here there is less friction, less convection, and there are no topographic interferences at all comparable with those on land. Hence we should expect to find the winds even at the surface blowing more nearly parallel to the isobars, and an inspection of marine synoptic weather maps indicates that this is true, the average inclination being about 10°. This means that the veering of winds with altitude is about 20° less over ocean than over land surfaces. In a similar manner velocities are affected, with the result that they are higher on the sea than on land, that is, they more nearly approach true gradient velocities.

It has already been stated that observations show above land an increase of about 100% in velocity within the first 500 to 1,000 meters (1,600 to 3,300 ft.). Now, surface winds at sea are nearly twice as strong as those on land. Hence the increase with altitude over the sea is much less than over the land. In other words, a transatlantic pilot would not need to fly as high as would a transcontinental pilot in order to derive the greatest possible assistance from the winds; and, conversely, in the case of opposing winds, there would be less advantage in flying at a low altitude over the ocean than over the land. Whatever the wind direction, whether favorable or unfavorable, flying at low levels above the sea would be less dangerous than at similar levels above the land, because the air there is, in general, less turbulent or bumpy. Near Newfoundland, however, considerable trouble from this source has been experienced. Bumpiness here occurs under conditions quite the reverse of those that produce fog, marked instability being caused when cold air from the north passes over the Gulf Stream or other relatively warm coastal waters. The central and eastern parts of the Atlantic appear to be compara-

tively free from bumpiness, except locally at times in connection with thunderstorms.

Frequency of days favorable for transatlantic flight. Such, in brief review, are the weather conditions over the North Atlantic in so far as they affect flight between the United States and Europe. It seems worth while to attempt an appraisal of these conditions in terms of their favorableness or unfavorableness for flight, but such appraisal must necessarily be relative, depending upon the aircraft employed, particularly their cruising speed and radius.

Table 20. Average Number of Days, Excellent (E), Good (G), Fair (F), and Poor (P), for Transatlantic Flight from Newfoundland to Ireland, Newfoundland to Portugal, Ireland to Newfoundland, and Portugal to Newfoundland

	Newfoundland to Ireland				Newfoundland to Portugal				Ireland to Newfoundland				Portugal to Newfoundland			
	E.	G.	F.	P.	E.	G.	F.	P.	E.	G.	F.	P.	E.	G.	F.	P.
January	8	7	4	12	5	4	8	14	0	1	2	28	3	3	4	21
February	3	7	4	14	2	7	4	15	0	0	0	28	1	1	2	24
March	3	7	4	17	3	6	6	16	1	1	1	28	0	3	3	25
April	2	5	8	15	1	6	7	16	0	2	3	25	0	2	6	22
May	5	7	4	15	3	8	8	12	0	2	2	27	1	1	3	26
June	2	8	6	14	1	5	5	19	0	2	2	26	0	2	5	23
July	6	7	8	10	2	6	11	12	1	2	5	23	1	3	8	19
August	5	8	7	11	3	5	7	16	0	1	1	29	0	2	4	25
September	3	6	6	15	3	5	8	14	1	1	1	27	1	2	4	23
October	3	8	5	15	1	8	7	15	0	0	0	31	0	3	3	25
November	1	5	6	18	0	6	5	19	0	1	1	28	0	4	3	23
December	2	9	5	15	2	9	6	14	0	1	0	30	0	2	1	28
Annual	43	84	67	171	26	75	82	182	3	14	18	330	7	28	46	284

In preparation for the projected flight of the NC seaplanes in 1919, an analysis was made of daily weather charts covering a period of 10 years, the basis of classification being as follows. An *excellent* day is one on which assisting winds prevail at practically all points along the route so that the advantage in time, assuming the aircraft has a cruising speed of 90 to 100 miles per hour (40 to 45 m.p.h.) is 3 hours or more; a *good* day is one on which assisting winds predominate,

although head or cross winds prevail part of the way, the assistance giving a gain in time of 1 to 3 hours; *fair,* one on which the proportion of favoring winds is about the same as that of head or cross winds, so that the time required for a flight is nearly the same as if there were no winds whatever; and *poor,* a day on which head or cross winds predominate or one on which very stormy conditions prevail. The results of this classification appear in Table 20.

Table 21. Average Number of Days, Monthly, Seasonal, and Annual, Favorable for Transatlantic Flight from Newfoundland to Ireland, Newfoundland to Portugal, Ireland to Newfoundland, and Portugal to Newfoundland

	Newfoundland to Ireland	Newfoundland to Portugal	Ireland to Newfoundland	Portugal to Newfoundland
January	15	9	1	6
February	10	9	0	2
March	10	9	2	3
April	7	7	2	2
May	12	11	2	2
June	10	6	2	2
July	13	8	3	4
August	13	8	1	2
September	9	8	2	3
October	11	9	0	3
November	6	6	1	4
December	11	11	1	2
Spring	29	27	6	7
Summer	35	22	6	8
Autumn	27	23	3	10
Winter	36	29	2	10
Annual	127	101	17	35

Dropping from further consideration the two classes fair and poor, and combining the first two classes into one group as constituting all of the days that are favorable for transatlantic flight, we obtain the results indicated in Table 21.

From these two Tables it is at once apparent, as was to be expected, that but little assistance from winds can be gained

for the westward trip along either the northern or the southern course. For the eastward trip, however, such assistance may be expected approximately one-third of the time, the percentage of favorable days being slightly greater along the northern route, due to its lying entirely within the region of the prevailing westerlies. A detailed study of the data upon which these Tables are based shows that favorable days occur on the average along the northern route 35% of the time, with extremes in different years of 25% and 47%; along the southern route the average is 28%, and the extremes 20% and 39%. When considering the monthly values, we find very large variations in the same months for different years. For example, in July, 1906, there were 28 favorable days for the trip from Newfoundland to Ireland, whereas in July, 1907, there were only 4. This and several similar cases give emphasis to the statement previously made that pressure systems over the oceans are slower moving than over the continents. Persistence of certain pressure types, with little change from day to day, is a marked characteristic of conditions over the Atlantic and should give no little comfort to an aviator who is about to undertake a flight, after having waited for days or perhaps weeks for a favorable opportunity to start.

The foregoing classification has been based on the assumption that the flying level is about 500 to 1,000 meters (1,600 to 3,300 ft.) above the surface. At greater altitudes, as already shown, the percentage frequency of westerly winds rapidly increases and, therefore, the percentage of favorable days for an eastward flight would become larger, probably increasing to 70% or more at the 3-kilometer (10,000 ft.) level. Conversely, the percentage of favorable days for a westward flight would decrease although it is difficult to imagine a much smaller percentage than that indicated in the table. The whole question as to the altitude most suitable for flight is still largely in the experimental stage, and the solution depends upon a thorough analysis of the various factors that enter

in. For example, it is frequently found that the greatest wind assistance would be realized at an altitude of 5 or even 8 to 10 kilometers (16,000, 26,000, and 33,000 ft., respectively), but, on the other hand, the greater tenuity of the atmosphere at those levels would reduce the efficiency of the engine, while the lower temperature and lack of oxygen would add to the discomfort of the aviator, thus making such altitudes prohibitive. Probably at the present time the most favorable height, all things considered, for transatlantic flying is between 1 and 3 kilometers (3,300 and 10,000 ft.) above the surface for the eastward trip and about 500 to 1,000 meters (1,600 to 3,300 ft.) for the westward trip.

Perhaps as good an index as any other of the rare occurrence of good flying weather is the fact that, with one notable exception, namely, Col. Charles A. Lindbergh, those who have essayed transatlantic flight have waited days, in some cases weeks, for favorable conditions, and even those conditions have been far from ideal. In every case stormy weather and fogs were encountered on some portion of the trip. And this would be true in general. Days with assisting winds can readily be selected, but it is doubtful if there are 10 days in a year on which conditions otherwise are really favorable on more than half of any northern route. On the southern routes, something like 30 days would probably be the outside limit. This number, as already hinted, would increase considerably for a route by way of Bermuda and the Azores or still farther south, so far as general weather conditions are concerned, but here we have the greater distance to contend with.

Conditions during Lindbergh's flight. Because of the great historic interest of Colonel Lindbergh's flight from New York to Paris, it seems worth while to review briefly the weather conditions that prevailed during that flight. At 8 P.M. (75th meridian) of May 19, 1927, a ridge of high pressure extended from Bermuda to the British Isles. Thus, wind conditions were favorable, but there was low pressure central

over Labrador which was likely to give thick weather east of Newfoundland. These conditions are shown in Figure 78.

Colonel Lindbergh left at 6:52 A.M. (75th meridian time) of the next morning and landed in Paris at 4:21 P.M. (also 75th meridian time) May 21. Figures 79 and 80 indicate the meteorological conditions that he encountered. There was little more to be desired so far as winds were concerned. They

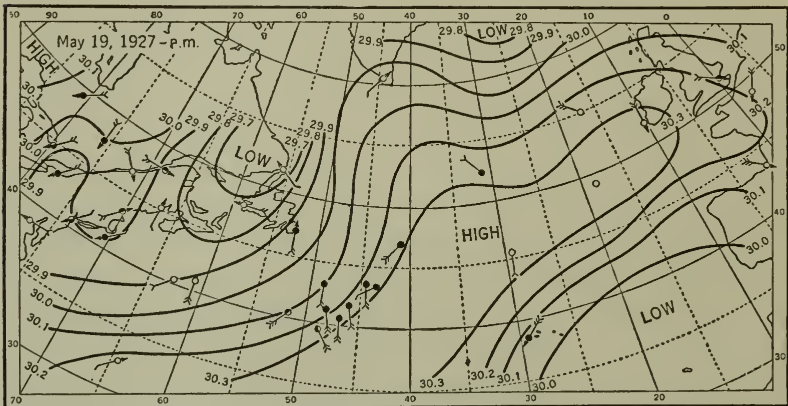

Figure 78. North Atlantic Weather Map, 8 P.M., 75th Meridian Time, May 19, 1927

Explanation: Isobars show corrected barometric readings in inches of mercury; 1 in.=25.4 mm.=33.9 mb. Arrows fly with the wind. Number of feathers indicate force, Beaufort scale. Open circles indicate clear; half-closed circles, partly cloudy; closed circles, cloudy; two dots, rain; three parallel bars, fog. High, center of high pressure; Low, center of low pressure.

were, in fact, very nearly as good as those that speeded Alcock and Brown across in June, 1919. As with them, however, Lindbergh's flight was attended by numerous meteorological hazards, including fog, ice, and snow. And so it has been in practically all of the attempts.

In the ill-fated flight of Nungesser and Coli, wind conditions were reversed, as shown in Figure 81. Providing the fliers kept to the north of the low pressure and stayed at a low altitude, they would undoubtedly have had help from the winds until near the American coast, but they would almost certainly have encountered heavy cloudiness, also snow, and ice.

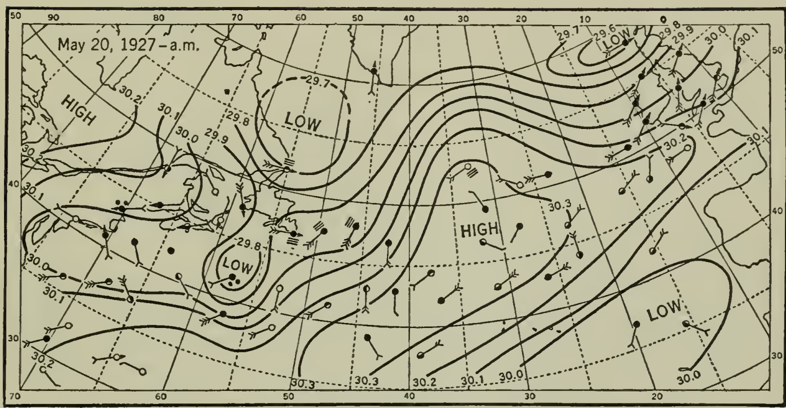

Figure 79. North Atlantic Weather Map, 8 A.M., 75th Meridian Time, May 20, 1927

For explanation of symbols, see legend under Figure 78.

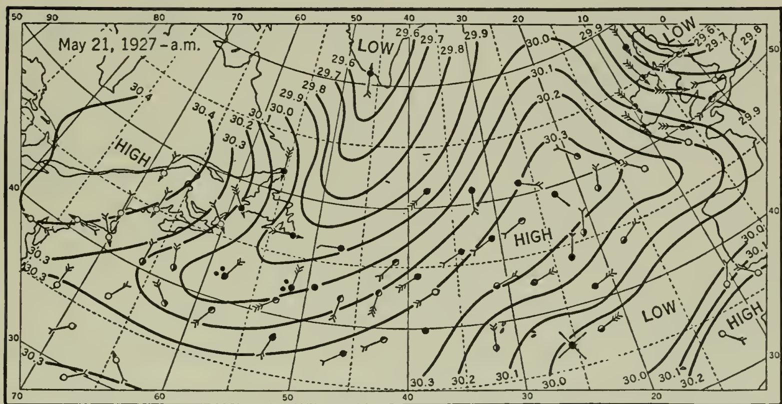

Figure 80. North Atlantic Weather Map, 8 A.M., 75th Meridian Time, May 21, 1927

For explanation of symbols, see legend under Figure 78.

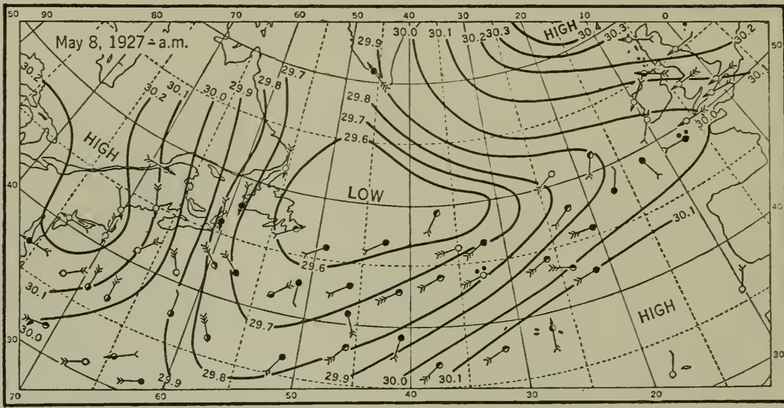

Figure 81. North Atlantic Weather Map, 8 A.M., 75th Meridian Time, May 8, 1927

For explanation of symbols, see legend under Figure 78.

In order that transatlantic flight may succeed on anything like a regular schedule basis, there will be required:

1. Much greater cruising radius than at present, or landing stations en route, such as the proposed floating airports.
2. Frequent, regular reports from ships at sea, containing information concerning surface weather and upper winds.
3. Dependable two-way radio communication between aircraft and earth, by means of which the pilot and meteorologist may be kept in constant communication with each other.

Flying in the Arctic

Meteorological information for the regions along the margin of the north polar zone is fairly complete, but little is known as to conditions above latitude 80°. Only a brief general statement can be made at this time.[4]

[4] Somewhat detailed discussions are contained in Hann's "Handbuch der Klimatologie," Vol. 3, pp. 588-677, 1911 ed.; and in Ward's "Climate," pp. 151-177, 1918. Additional data may be found in the *Arctic Pilot*, H. O. 137; *Arctic Pilot*, Hydrographic Dept., B. A.; Bartholomew's "Physical Atlas," Vol. 3; *Nautical Meteorological Annual of the Danish Meteorological Institute;* and the reports of Greely, Peary, Stefansson, and others.

Temperature. From all available data, H. Mohn[5] has deduced the following mean temperatures, in °C. and °F., for different latitudes:

Latitude, N	60°	65°	70°	75°	80°	85°	90°
Centigrade							
January	−16.1	−23.0	−26.3	−29.0	−32.2	−38.1	−41
April	− 2.8	− 7.3	−14.0	−18.8	−22.7	−26.5	−28
July	14.1	12.4	7.3	3.4	2.0	0.3	− 1
October	0.3	− 4.1	− 9.3	−14.1	−19.1	−22.2	−24
Year	− 1.1	− 5.8	−10.7	−14.7	−18.1	−21.2	−22.7
Fahrenheit							
January	3.0	− 9.4	−15.3	−20.2	−26.0	−36.6	−41.8
April	27.0	18.9	6.8	− 1.8	− 8.9	−15.7	−18.4
July	57.4	54.3	45.1	38.1	35.6	32.5	30.2
October	32.5	24.6	15.3	6.6	− 2.4	− 8.0	−11.2
Year	30.0	21.6	12.7	5.5	− 0.6	− 6.2	− 8.9

In winter the prevailing tendency for temperatures to decrease with increasing latitude is broken by two areas of extreme cold in northern Siberia and in northern Greenland, where the average is lower than at the pole itself; in summer the region in Siberia is warmer than any other at the same latitude.

Observations at Fort Conger, Grinnell Land (lat. 82° N, long. 65° W) during 1881–1883 gave as the highest temperature 12° C. (54° F.) and the lowest −52° C. (−62° F.). In Franz-Josef Land, about the same latitude but in *east* longitude between 50° and 67°, several series of observations by different expeditions showed a maximum of 12° C. (54° F.) and a minimum of −46° C. (−51° F.). Lowest temperatures usually occur in calm weather as a result of active radiation. It seems likely that on such occasions there is an inversion

[5] In *Meteorologische Zeitschrift*, 1906, p. 47.

above the surface, as a wind almost invariably raises the temperature appreciably.

Winds. The cyclones of temperate latitudes in many instances reach and travel along the margin of the polar zone but seldom very far within it. Hence, the winds at high latitudes, 70° to 85° N, are prevailingly from an easterly direction. Thus, the Franz-Josef Land data for 1894–1896 show northeast to southeast winds 39% of the time, a high value in view of the fact that calms prevailed 27% of the time. At Fort Conger the wind for the year averaged about S 65° E, with a slight north component in winter and a strong south component in summer. Here also the percentage of calms was high, 35%, with a marked seasonal variation from less than 5% in summer to about 75% in winter. Gales were apparently not frequent at this place, although there was one case of 60 miles per hour (27 m.p.s.) from the northeast and another of 52 miles per hour (23 m.p.s.) from the southwest, both in winter. The average velocity was somewhat greater in summer than in winter owing to the preponderance of calms in the latter season.

There is very little information for the regions north of latitude 82° N, but that little is in agreement with theory that the state of the atmosphere is one of comparative calm. Captain Sir Hubert Wilkins, N. C., stated[6] that, although his flights did not take him anywhere near the Pole itself, high winds were found only near the great land masses. At his farthest distance from shore comparatively calm air was experienced, and north of Greenland he got into still air conditions.

Observations made by other expeditions have led to the same conclusion, namely, that the Arctic is one of the least stormy large areas in the world. The cyclones of middle latitudes seldom extend far into this region, but it is to be noted that, even in the case of those that do go there and assuming

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[6] *Journal of the Royal Aeronautical Society*, October, 1928, pp. 885-900.

that they retain much of their intensity including a steep pressure gradient, nevertheless the winds would not be strong owing to the rapid increase in the deflective force of the earth's rotation. (See Chapter 1, section on "Pressure and Wind.")

Cloudiness, fog, and precipitation. Such data as are available indicate that cloudiness is somewhat less than in temperate latitudes and that its seasonal variation is quite the opposite, with a maximum in summer and a minimum in winter. The averages for these two seasons are about 80% and 50%, respectively. In winter, clear weather often prevails for several days at a time.

Fog occurs quite generally in summer and is largely responsible for the high percentage of cloudiness which the records show for that season. It is particularly prevalent along the borderline between land and water areas and in the vicinity of ice packs. During the remainder of the year, particularly the winter but including also most of autumn and spring, there is very little fog; when it does occur in these seasons, it is usually of the radiation type and therefore very shallow. Even in summer, when fog is frequent, its height probably is seldom in excess of 1 kilometer (3,300 ft.).

Precipitation occurs mostly in the form of fine, dry snow and its water equivalent is probably less than 250 millimeters (10 in.) a year, as a rule. At Fort Conger it averaged about 150 millimeters (6 in.). "There is no month without some snowfall. During winter the snow cover grows to a very heavy mass through the condensation of atmospheric moisture on its surface, the temperature of which is mostly below that of the air. This form of precipitation it is not easy to measure."[7] Some trouble was experienced by the *Norge I* during the first Polar flight in May, 1926. Near the Pole, fog was

[7] B. M. Varney, "Meteorological Conditions in the Eurasian Sector of the Arctic," *Monthly Weather Review*, Vol. 53, pp. 475-479, November, 1925.

Abstract of: Das Luftschiff als Forschungsmittel in der Arktis. Published by the International Society for the Exploration of the Arctic Regions by Means of the Airship, Berlin, 1924. A Summary of Conclusions Presented by Karl Schneider, A. Berson, L. Breitfuss, M. Robitsch, R. Süring, A. Wegener, and K. Wegener.

encountered and ice formed on the gondolas and rigging causing an increase of weight and other difficulties.[8] On the other hand, Captain Wilkins had found[9] very little trouble from ice in the course of his 18,000 miles (30,000 km.) of flying within the Arctic circle. In general, it is probable, notwithstanding the experience of the *Norge*, that the temperature is too low and the condensed moisture in the air therefore too light and "dry" to cling appreciably to aircraft surfaces.

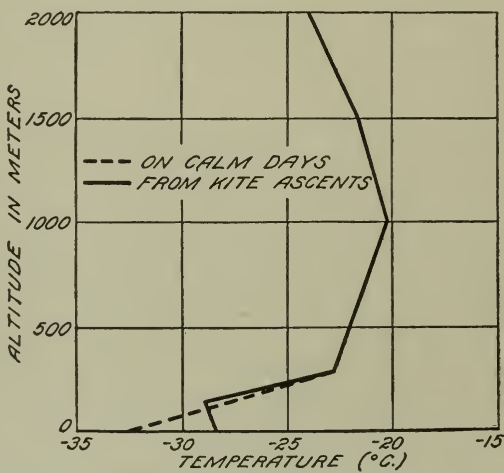

Figure 82. Average Upper Air Temperatures, November to March, as Observed with Kites on the *Maud* Expedition

To convert meters to feet, multiply by 3.3; °C. to °F., multiply by 1.8 and add 32.

Upper air conditions. A notable series of observations with kites and pilot balloons was made during the Arctic cruise of the *Maud* from August, 1922, to August, 1924. Dr. Sverdrup[10] in charge of the scientific work of this expedition, has summarized the results for the colder months of both years which were spent in about 75° N latitude and between 155° and 175° E longitude. Figure 82 shows the temperature

[8] S. P. Peters, "The Polar Flight of the Airship *Norge I*," *Meteorological Magazine*, Vol. 61, pp. 102-105, June, 1926, London.

[9] *Loc. cit.*

[10] H. U. Sverdrup, "The North-Polar Cover of Cold Air," *Monthly Weather Review*, Vol. 53, pp. 471-475, November, 1925.

distribution and is characteristic of conditions observed in nearly all flights. There was, of course, variation in the actual values on different days, but the outstanding features were continuously present, namely, a layer of very cold air from the surface to about 140 meters altitude (460 ft.); a second layer of the same thickness, in which the temperature rapidly rises; a more gradual rise in the next 700 meters (2,300 ft.); and finally, a region above 1,000 meters (3,300 ft.) in which the temperature decreases with altitude.

Observations of temperature were made with kites and therefore only on days with wind. The solid curve in the figure shows that mixing by the wind extends to a low altitude only. In 52 of 60 cases this altitude was less than 200 meters (660 ft.), and in no case more than 650 meters (2,100 ft.). Evidently, then, the cold layer close to the ice represents air which to a great extent is isolated from the free atmosphere.

On calm days the surface temperature was considerably lower than on days with wind. As shown by the broken curve in the figure, the temperature probably increases quite regularly on such days from the surface to approximately the height 140 meters (460 ft.) which represents the limit of air mixing on windy days.

Observations of wind indicated a rapid increase of velocity and a marked turning of direction to the right between the surface and the inversion layer. Above this level, for several hundred meters both velocity and direction remain practically constant. The average velocity at the surface was about 5 meters per second (12 m.p.h.) and in the upper levels, about 12 meters per second (27 m.p.h.).

A feature of great interest is, to quote Dr. Sverdrup, "that the character of the vertical distribution is independent of the direction from which the wind blows, and this is evidence that the same conditions prevail over wide areas. This is confirmed by the results of several ascents with captive balloons and kites made at Cape Chelyuskin (77° 32′ N latitude, 105°

40′ E longitude) in the spring of 1919, and by the results of kite ascents during the winter 1924–1925 off Bear Islands (70° 43′ N latitude, 162° 25′ E longitude), which all show the same features. Considering the uniform character of the meteorological conditions over the Polar Sea, it seems justified, therefore, to draw the final conclusion that the whole Polar Sea in winter is covered by a thin layer of cold air which to a great extent, is isolated from the warmer air above." This condition develops in the autumn and prevails during the greater part of spring, thus existing through the major part of the year. In July and August, the ice is melting and the temperature at and near the surface is therefore in the neighborhood of freezing, but "above an altitude of 150 to 200 meters (500 to 650 ft.) the mean temperature according to the kite ascent seems to be higher, partly on account of convection and partly perhaps on account of direct absorption."

On the whole, then, conditions *within the Arctic* are quite favorable for flight, far more so than those over the north Atlantic, at any rate during winter. There are practically no storms and very few high winds over the Polar basin. The weather is relatively clear except in summer, when considerable fog occurs but this seldom extends to a height above a kilometer or a little more than half a mile. Little precipitation occurs, and the moisture in the atmosphere as a rule is in a form that would seldom result in causing heavy deposits on aircraft. Thunderstorms are rare and in some sections probably do not occur at all. Finally, the existence of an inversion layer at flying levels would prove of distinct advantage to airships, besides rendering travel more comfortable.

The greatest obstacle to Arctic flying, from a meteorological viewpoint, appears to be, not the conditions within the Polar basin, but on its rim. Getting into the Arctic through Alaska or northern Canada and out again through Siberia or northern Europe, and vice versa, is the first big problem to overcome, so far as weather is concerned.

CHAPTER 13

ICE FORMATION ON AIRCRAFT

By C. George Andrus

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Before the days of air transport, only random attention was paid to a weather activity that has since been rated as the greatest obstacle to scheduled flights in winter. This weather phenomenon is the collection of ice on the exposed portions of aircraft, where they are subjected to the sweep of air currents carrying much moisture. Glaze has been observed on mountain peaks; meteorological kites and wires have brought down to earth examples of this glazing in clouds, but its serious nature has only recently become a subject of intense importance and study.

It is generally understood that ice as a serious menace to aircraft is derived from rain which is encountered while it falls through the air; the process is assumed to be that which is more or less frequent in the northeastern part of the United States and known as the ice storm. Actually this is the result of a freezing rain, with the immediate congealing on all exposed objects of the drops of rain when they strike. The greater part of the ice collected on aircraft while in flight is, however, not due to this type of weather, but to a more common condition and one difficult to avoid. The ice storm (glaze) is but one of many atmospheric activities which produce ice, and because it is easily recognized by observers on the ground, it is one which is readily and usually avoided by careful fliers.

The action of aircraft in rushing through air masses at high speeds appears to be a large factor in determining where and how the ice will form. The action is different on airplanes from that on airships; the resultant hazards are equally different and will be separately considered.

Lighter-than-air craft. The action of ice on lighter-than-air craft has been less widely and frequently experienced and studied, but the fact that ice may form a veneer, sometimes smooth and sometimes rough, over the forward portions of the dirigible balloon type of airship is well established and has caused forced landings. Such an accumulation of ice is one danger, represented as excess weight, since any moisture carried on the outside of the envelope is undisposable ballast, not subject to the control of the navigator. Ice forming on the propellers of airships represents a great danger if they are so located that masses of loosened ice may be thrown against the envelope, thus causing structural damage. The collection of ice on the hull precedes, by a fair interval, sufficient accumulation on the control surfaces, which are well aft, so that the disabling of the ship by excessive loads of ice is likely to occur before dangerous loss of maneuverability results from ice on the control surfaces, but both dangers should be considered.

Free balloons. On free balloons, only that type of ice collection which is found in the ice storm, i.e., freezing rain, is considered dangerous. The balloon forces itself against currents of air only momentarily while passing from one stratum into another of different direction; hence, it collects only that quantity of ice which falls on it as precipitation. The small excess load created by ice accretions while rising through subcooled clouds could be readily offset by small expenditures of ballast.

Heavier-than-air craft. On heavier-than-air craft the leading edges of all exposed parts take the first ice accumulations, because here the air is cleaved and the impact of water

or ice particles is most pronounced. If the ice is forming from freezing rain, the accretions build up to the rear after starting at the leading edges. If some sleet is intermingled with the freezing rain, it is imprisoned by the latter,—a rough and rapidly developing coat of ice results. Snow, mixed with rain, while not common, may have the same effect.

The coating of ice may take many forms and show various surfaces. It may be whitish or clear in color, depending apparently on whether it freezes slowly or rapidly, respectively. Some clear coats have been attributed to freezing rain, but this does not always seem to be the case. It may take many forms and show a variety of stalagmitic protuberances or it may be deposited as a smooth or rippled coat. Flaky, granular, clotted, and rippled forms have been observed, but their relation to the type of atmospheric condition responsible for the ice is not clearly demonstrated. Usually the ice is whitish in color but hard and massive; close scrutiny is necessary to discover it on some occasions and photographs of it have been notably poor. Particularly rough and barnacled surfaces usually result from sleet and snow which have become caught in the freezing water. Usually the ice accretions do not extend back on the wings more than one-third of the front-to-rear distance (chord direction), except in freezing rain conditions, but it may completely incase the smaller parts or wires and very materially increase their resistance.

Chief effects. The important effect of the ice collection on airplanes is that the efficiency of flight is immediately reduced, because the aerodynamic characteristics of the supporting wings are changed. The loss of aerodynamic efficiency also occurs to airships, but in a smaller degree. Practically all other meteorological conditions affect the navigation of the craft, but have no ill effect on the performance of flight. Several factors are involved in this loss of efficiency, the importance of which varies with the type of craft (whether airplane

or airship), its size, shape, distribution of exposed parts, and general stability.

On airplanes, ice accretions reduce the ability to maintain flight, and sometimes they form so quickly that the danger becomes serious at a time when conditions render navigation difficult. The ill effects of ice deposit are: (1) increase of drag (the resistance offered by the surfaces of plane and exposed parts to smooth passage through the air); (2) decrease of lift; (3) dangerous stresses and vibration caused by ill-distributed drag and unfaired surfaces; and (4) added load.

The increase of drag is due to two important causes: (1) the direct enlargement of wings, struts, wires, etc., thus opposing greater area to the wind; (2) the rough or rippled surface of the ice formation which adds materially to the surface friction.

The decrease of lift results from altered wing curvature. The shoulder of ice which usually forms first and foremost on the upper portion of the leading edge, changes the lift of that airfoil materially; the process being rapidly aggravated by further increase in the size of the shoulder.

Vibration and stresses are dangerous, especially when greater drag and more weight are being added by the ice. Unless the airplane is already heavily loaded, the actual weight of the ice itself is not a serious danger, since if it were carried in the cargo space of the plane, it could be transported easily, but it is the location of the added weight that aggravates the other troublesome factors. Propeller blades collect ice unequally, and the eccentric center of mass thus established is dangerous at the speeds of modern aircraft engines.

On the airship the greatest danger seems to be the poorly disposed load that is carried on the envelope. The larger portion of the ice that collects forward and on the upper parts adds structural strains which may collapse a nonrigid or semi-

rigid type of airship. Propeller-cast masses of ice may puncture the gas containers or may foul the controls.

On both airplanes and airships, outside radio antennae may be affected adversely by ice accretions. The weight of the ice may break the wire or its thickness may offer too much air resistance.

Unfavorable conditions for navigating the craft usually attend ice-accretion conditions and seriously aggravate the danger. Low ceiling and fog are two of the most serious difficulties of flight and are usually present in pronounced form when ice is being accumulated. Some of the measures taken to aid in guiding airplanes through fog are dependent on complete control of the plane, and this control may be upset by ice. It is also likely that devices which rob the fog and cloud of the perils of blind flying will encourage more flying through conditions which produce ice. The danger of planes meeting ice conditions is therefore on the increase. Its study and the search for preventive devices are most important.

Subcooled water droplets in clouds. The most recurrent condition which produces ice is the subcooled wet cloud with temperatures below the freezing point of water. In some clouds, such as the cirrus type, the particles are known to be fine crystalline flakes and spicules, as indicated by halos and related phenomena which can be produced only by ice crystal action on light waves. The majority of clouds, however, contain moisture in tiny droplets whose characteristics are the same as those of droplets found in thick fogs. In fact, within the clouds the observer finds himself surrounded by what appears to be dense fog, at times surpassing the opacity of the densest fogs of the surface since condensation may be proceeding at a rapid rate, a condition never occurring within fogs on the ground. These wet clouds exist at temperatures through a range extending from well above freezing down to several degrees below zero (lowest observed, −23° C. or −9° F.). Only in clouds whose temperature is below freez-

ing do aircraft take ice. But it is also true that in any such wet subcooled clouds there is potentially the ice peril, unless the cloud is composed of snowflakes or crystals of ice in some fine form.

Moist snowflakes. Another condition conducive to ice formation is that of moist snowflakes falling through air at temperatures just below the freezing point. It is not frequent, but there are occasions when flight is interfered with by the collection of ice which is really frozen slush. The action comprises instantaneous freezing of the moisture in the flakes, when they strike the edges of airplane parts. Usually the condition is local and a pilot who can remain aloft for a brief period may find relief by reaching areas where the snow is entirely dry and unable to cause ice.

Glaze. Another condition conducive to the formation of ice is that which is usually termed the ice storm, or glaze. Then the plane receives a coating of ice similar to that which forms on ground objects in an ice storm. Occasionally sleet is mixed with this freezing rain and aids in promoting rapid growth of an ice coat. If the precipitation is wholly in the form of sleet, there is no danger of taking ice, although the possibility that, without much warning, the sleet may change to rain and sleet must be borne in mind. The distinction between glaze and sleet should be clearly recognized. Glaze sometimes is popularly but erroneously called "sleet": it is a coating of ice on objects due to the freezing of rain *as it strikes those objects.* A deposit of glaze over a considerable area constitutes an "ice storm." Sleet is frozen rain; the freezing having taken place in the air, before the raindrops strike terrestrial or other objects.

Structure of atmosphere during ice formation. The structure of the atmosphere during the three types of conditions conducive to ice is of interest, but many of the details are still being sought by the use of recording instruments on

airplanes and kites. The best examples of subcooled clouds may be found to leeward of the Great Lakes in the early winter months, whenever a cold northwest wind passes inland, after crossing these lakes and absorbing masses of vapor from the relatively warm lake surfaces. The air temperature may fall to many degrees below freezing, while the moisture retains its original liquid state. The disturbance created by the surfaces of the airplane in forcing through these masses of subcooled water droplets apparently provides the impulse to crystallize them and a deposit is forthwith made on the disturbing parts of the plane. The fact that many violent snow squalls fall from clouds in which ice may be taken lends support to the belief that a large percentage of all clouds which produce substantial precipitation are composed of liquid particles. Any convective or turbulent action which will form clouds is particularly likely to produce "wet" ones. There are numerous instances of "clouds" of snowflakes. Within such formations the pilot finds himself in a dense mass of flakes but is not surrounded by the opaque "fog" which is usually observed within true clouds. Obviously there are dangers in all clouds, because it is impracticable to distinguish which are snow masses and which are water droplet masses, whenever the temperature on the ground is so low that the normal lapse rate is likely to result in temperatures of freezing, or below, at the cloud level.

The structure of the atmosphere for freezing rain has been carefully studied from aerological observations. The conclusions reached by Meisinger and others briefly assume a condensation stratum in the upper air at some moderate elevation, higher than that which causes low clouds or scud masses. Condensation reaches the rain stage or the snow stage at this high level and precipitation results. The falling raindrops in their descent finally reach the lower layers of the air where temperatures in a northerly wind which exists for the first thousand or so feet (300 m. plus) are below freezing. In

this lower layer the raindrops are chilled to below freezing but crystallization is suspended. As soon as these drops strike a cold object on the ground, they solidify as a congealed layer of glaze. The same process occurs when the condensation is in the snow stage except that the snowflakes are first melted to raindrops and then these follow the same process of freezing at the ground.

While devices and plans are being developed to attempt to prevent ice from forming and to dispose of it at frequent intervals after it forms, the part of prudence will always be to avoid, as much as possible, any flying which will take the aircraft into regions where ice will form. These regions will depend on many factors; a few of the main ones follow.

Any area of precipitation which occurs with ground temperatures below 40° F. (4° C.) is likely to involve flying in ice-formation conditions. This is especially true if the course lies across country with some sections much higher than others. Sleet and freezing rain areas are dangerous and should be avoided as should be those areas wherein these conditions are predicted. Any area of low overcast, or nearly overcast, cloudiness presents a danger if the clouds are sufficiently low to require approaching their level in flight. Snow squalls are hazardous, especially when they attend a wind shift or line squall. In a general sense, it is desirable to examine carefully all the weather elements in any area which shows temperatures on the ground near or below freezing and any tendency to an increase in the amount of clouds or precipitation.

Precautions to observe. Once aware of the potential danger in certain areas, as shown by the weather map, the pilot may be enabled to plan a flight in safety in the light of up-to-the-minute weather reports along the course. The following plans of action are given, not as recommendations but to indicate examples of the methods: they may be helpful in negotiating an escape from unexpected encounters with ice.

1. Flight in sleet, assuming that the sleet is entirely "dry,"

and will remain so to the destination; such flight will be performed at the lowest safe altitude where the sleet is most likely to have become completely dry because of the long fall through subfreezing air.

2. Flight up through fairly thin but ice-producing clouds, then over their tops to destination. This course assumes able handling of the plane in blind flying, and careful navigation; also, information as to the thickness of the ice-producing cloud. It is not suitable for adoption through snow squalls or other convective developments because the ice clouds are not then stratified and may extend to considerable heights.

3. In sleet or ice storm conditions, an immediate climb to the upper warm layer which is the basic requirement for these storms, there to fly in or above warm clouds whose temperature may be as high as 50° F. (10° C.). This is attended by the danger of becoming lost in the varied wind directions and velocities and will usually be a "rough air" flight. As a strict rule from which little deviation should be allowed, except to pilots of known ability and experience, it is best to remain on the ground unless flight can be carried through to destination without the aircraft being taken through clouds, precipitation, and snow squalls. Consideration must be given to the height of the terrain and the relative proximity of any cloud ceiling to high points along the course.

Instrumental warnings. The use of instruments mounted on the aircraft to give warning of the ice peril is dependent on several factors, foremost of which is the experience and intelligence of the pilot, and the proper exposure and calibration of the instruments. No instrument has been devised or is likely to be developed which will indicate directly or positively with a high degree of reliability that ice formation is imminent. Practically all the instruments would be temperature- and humidity-recording or distant-registering. Actually, they will show what the condition of temperature and humidity is at any time, although records from flights show that the latter

especially may be subject to sudden changes of wide extent. The temperature instruments will show what the temperature runs as an average at any level selected for flight. After a study of the weather map to determine whether the tendency toward the destination is to lower or higher temperatures, the readings during flight will show the likelihood of penetrating any clouds which may be found at a temperature which will be below freezing. The only gage point on such thermometers should be that at freezing. There is no foundation for the assumption that at some stated subfreezing temperature the ice danger is removed. It is true, however, that the quantity of ice appears to be less and that the ice forms more slowly at temperatures near 0° F. (−18° C.), and the general conclusion is that there is a gradual diminution in the ice danger with reduction of the temperature below freezing, the greatest accumulation and most rapid rate of accretion being found just below freezing.

Geographic and seasonal relations to ice formation. The question frequently arises as to whether certain geographic regions are exempt from the toll of ice-forming conditions. The answer is, of course, in the affirmative and the same answer is made to the query as to whether certain seasons are exempt. The ruling factor is the temperature of the air strata through which flight must be made. In that terrain, which requires attainment of considerable altitude for the crossing of mountain ridges, the temperature at the levels involved will be the controlling factor. Accessory to the temperature factor is the moisture content of these "critical" elevations (critical refers here to the necessity of attaining them for flight over terrain), for, without a quantity of moisture sufficient for condensation at freezing temperatures, or below, no ice is possible. Roughly, then, the limits of ice danger in both the geographic and the seasonal sense are those fixed by a temperature of freezing and a dew-point temperature of approximately freezing.

It follows that the drier sections, such as the Great Plains and southwestern portions of the United States, are less liable to have ice conditions than the areas in the vicinity of the Great Lakes and North Atlantic coast. Similarly, the Pacific coast regions have a variety of conditions which are preponderantly "wet" with high relative and absolute humidity, yet because of moderately high temperatures along the immediate coast, the ice hazard is small, but for flights over the coastal ranges the "ice" possibility is high owing to the altitude and consequent lower temperatures that are encountered.

Pressure distribution and ice formation. The pressure distribution as related to ice conditions is also a basis for the apprehension of danger from this source. The cold or polar front sides of Lows are usually well loaded with conditions cold enough for ice, and on the forward side of the Low the polar air may carry sufficient moisture to produce ice hazard. Occasionally the whole area of cloudiness in a Low may have temperatures below freezing, while at other times the skies may be clear where the temperatures are low, and cloudy to overcast elsewhere, thus rendering flights reasonably safe. That isobaric formation which shows a slowly retreating and deepening Low passing down the St. Lawrence valley, followed over the Lake region by westerly winds and slowly falling temperature is very favorable for ice formation, if the temperatures are less than 40° F. (4° C.). As the tendency would be for the weather to clear behind such a Low, were the lake influence absent, the dangers of flight in such a situation are sometimes scarcely recognized. As long as the gradient remains strong so that the southwest to northwest winds will be maintained with fair force, the snow squalls and ice conditions will continue during the winter months. Large Highs occasionally settle with their centers over the mouth of the St. Lawrence, and under this distribution overcast skies attend the northeast winds which are generated over the New England and northeastern portions of the country, and sometimes

desultory but tenacious rain spells occur. With temperatures near or below freezing these conditions are dangerously apt to produce ice, but as a rule the ice-producing clouds are fairly shallow, 1,000 to 2,000 feet (300 to 600 m.) in thickness, and occasionally offer breaks which are avenues to the less moist areas above them.[1]

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[1] References to chapter: "The Formation of Ice Upon Exposed Parts of An Airplane in Flight," and "The Formation of Ice Upon Airplanes in Flight," Two Technical Notes Nos. 293 and 313, National Advisory Committee for Aeronautics, Washington, D. C. By Thomas Carroll and William H. McAvoy.

"Danger of Ice Formation on Airplanes," Technical Memorandum No. 499, National Advisory Committee for Aeronautics, Washington, D. C. By W. Kopp, Lindenberg Aeronautical Observatory, Berlin. (Translated by the Daniel Guggenheim Fund for the Promotion of Aeronautics.)

CHAPTER 14

AIRWAYS WEATHER SERVICE

In the 13 chapters preceding this one, effort has been made to present and, to the extent necessary for their proper understanding, to explain all known facts concerning the phenomena of the atmosphere that bear a more or less direct relationship to flying. The numerous ways in which these facts can be and are applied and made use of have been indicated and discussed. Moreover, reference has been made frequently to the arrangements that are in existence for providing this practical or applied service. However, these references are scattered throughout the book. It seems well to present, in one collected though brief statement, those features of weather service for aeronautics which experience has shown to be essential. Details of organization are constantly changing and are not considered here; only the broad general outline and the "high lights" or landmarks of the picture.

Two types of service. Meteorology, as usually defined, is the science of the earth's atmosphere. It embraces, therefore, both climate and weather.

Climate is concerned with statistics and deals with the normal or average state of such elements as pressure, temperature, humidity, cloudiness, precipitation, sunshine, fog, storminess, visibility, and wind. A proper appraisal of the climate of a place or region must be based upon data covering a period of many years. The greater the length of this period the more accurate will be the appraisal.

The state of these same elements at a given time and place, or during a particular period and in a specified region, is what

constitutes weather. It can and does vary from a state of calm serenity to one of utmost peril to life and property.

Meteorology may also be considered from the viewpoint of theory and practice. In the former, the various phenomena of the atmosphere that are our daily companions are studied in an effort to get at the underlying laws governing our weather and its changes. Although the interest here results in part from a desire to increase the sum of human knowledge, the chief purpose is to make more effective its practical application. Today applied meteorology is definitely and actively associated with all lines of industrial and commercial activity, and thus we have such subdivisions as agricultural, horticultural, insurance, marine, and aeronautical meteorology. All of these are comparatively new, but perhaps the most recent is that branch which serves aeronautics. Certainly, its development, in the past 5 years at least, has been more spectacular and on a much larger scale than has that of any of the others.

Aeronautical meteorology, like the more general subject meteorology itself, deals with statistics, or climate, and with current service, or weather. Aeronautics has very definite relationships with both. Let us see what some of them are.

Statistics, or Climate

Statistical information for our present purpose may be divided into two classes: that needed in developing the ground organization, and that useful in determining regular flight schedules.

Ground organization. For the ground organization there should be included such climatological factors as frequency of different wind directions at the surface; average velocity of surface winds, classified by direction; frequency of strong surface winds, also classified by direction; and frequency of gusty winds, poor visibility, fog, haze, smoke, heavy precipitation, etc.

As a rule, there can be no great latitude in the location of airports, since these will necessarily be near the larger centers of population, and must be within reasonably easy reach of them. Little if any use can therefore be made of information concerning certain other climatological factors such as the frequency and intensity of thunderstorms, violent storms, and temperature extremes, since in a small area their variation would be unimportant.

On the other hand, there is in many cases, within comparatively small areas, considerable variation in wind conditions and especially in visibility. Gustiness is greatly increased by topographic irregularities, buildings, and trees. A site as nearly free from these as possible should be selected. Information as to frequency of different directions and velocities of surface winds is important in connection with the orientation of hangars and the layout of runways.

But by far the most important factor to be considered in selecting an airport site is visibility. The relative prevalence of haze and smoke, particularly the latter, is a function of the prevailing wind. In general, the selection of a site on the leeward side of a city should be avoided, other things being equal. However, primary consideration should be given to the occurrence of fog—the one condition that reduces the visibility to zero.

Fog frequency varies decidedly, in many cases, within small areas. Particularly is this true along the coasts of the Great Lakes and the oceans and in the neighborhood of rivers and small lakes. In general, all low-lying areas should be avoided, so far as possible.

In addition to wind and visibility, some attention should be given to the precipitation characteristics of a place. If heavy rains are frequent, the airport must be properly graded and drained. And if heavy snowfalls are to be expected, provision must be made for quickly clearing the runways. It is true that rain and snow do not vary much in amount within

a small area, but some parts of such an area would in many cases be better than others for resisting the erosive or softening effects of excessive rainfall and for quick clearing of heavy snow.

In the case of airports for the larger cities, sufficient data as a rule, are already available. In some instances, however, it has been advisable to make what may be called a local meteorological survey. Several of these have been made and others are now being carried on. Perhaps the most complete is the one for San Francisco which covered one year and was conducted by that city in cooperation with the Federal Weather Bureau. Elaborate equipment was installed at several proposed sites and observations were made in great detail, of fog frequency, ceiling, visibility, gustiness, and other meteorological elements. It is significant that the final selection of the San Francisco Municipal Airport was based solely upon the findings of this survey.

For the smaller cities and towns the problem is less difficult as a rule, the chief purpose, in many instances at least, being to provide intermediate landing fields on the major airways that will be available for emergency use. However, information concerning the average conditions at these smaller airports is needed and has been supplied and compiled by the Weather Bureau as part of a series of individual airway bulletins, published by the Department of Commerce. The meteorological data include a wind-rose and a brief summary concerning strong winds, fog, and heavy precipitation.

There has also been published a series of 48 bulletins, giving in more general terms the climatic characteristics of the several states. These contain sections on cloudiness, fogs, visibility, heavy rain and snow, ice in lakes and rivers, thunderstorms, surface winds, including frequency of strong winds, and upper air winds.

Schedule maintenance. Climatological factors useful in determining the most efficient flight schedules include resultant

winds at flying levels; frequency of different wind velocities at flying levels, classified by direction; frequency of widespread storms; frequency and intensity of thunderstorms; frequency of low clouds and fog; visibility; and general character of precipitation.

In determining flight schedules for any proposed airway, the most important datum is, of course, the cruising speed of the aircraft employed. To this must be added, or from it deducted, the resultant wind at different points along the route. This corrected value forms the proper starting point or basic datum for determining schedules. The operator of any service must decide what percentage of arrivals on time he will undertake to guarantee. It is then a comparatively easy matter to compute the schedules that, on the average, can meet this guarantee. The principal determining factor is the frequency of head and cross winds of various velocities, resolved into components parallel and perpendicular to the course. In general, a considerably faster schedule can be adopted in this country for eastward than for westward flights, since, as is well known, the upper winds are prevailingly from the west. Moreover, the upper winds in general increase in velocity with altitude; therefore, eastward flights should be at a higher level than westward flights.

Allowance should be made for a certain percentage of canceled flights. This percentage will vary in different parts of the country and will also have a marked seasonal variation. It can be determined quite closely by an analysis of such climatological data as the frequency of widespread storms, low clouds, fog, poor visibility, and heavy precipitation, especially snow. These conditions not only cause delays but occasionally prevent flights altogether.

Current Service, or Weather

Statistical information has its place in aeronautics, and a very important one, as has already been seen. Yet, in a very

real sense, it may be said to be only preliminary to the chief service that meteorology can render, namely, furnishing up-to-the-minute weather reports and forecasts for each and every flight. Nothing short of this will do. The experience of the past few years is conclusive.

In order to gain public confidence and support, and to demonstrate its right to a prominent place in the industrial and commercial life of the world, flying must be both safe and efficient. Many factors enter in, including design and construction of aircraft, facilities at airports, marking and lighting of airways, instruction of pilots, licensing of aircraft, and adequate weather service. Some of these are chiefly concerned with safety, others with efficiency.

Safety. Until a comparatively recent time, weather was generally thought to be responsible for quite a large percentage of aircraft accidents. This is no longer true. Weather service has already been developed to the point where accidents from weather rarely occur, *if the warnings are heeded.* It is significant that, in Report No. 308, "Aircraft Accidents," issued by the National Advisory Committee for Aeronautics, weather as a cause of accidents occupies an inconspicuous place in the "miscellaneous" section. It is of interest also to note that in an analysis of accidents published in the 1930 Aircraft Year Book by the Aeronautical Chamber of Commerce of America, Inc., only 5.02% of accidents were caused by weather. Of course, even this number is too high and must be reduced, but the fact remains that weather is now one of the minor causes of accidents.

Efficiency. The case is entirely different when we come to efficiency. Here the weather service is the controlling factor. It determines whether the flying along an airway will be of the haphazard, hit-or-miss variety or of the type that takes advantage, in unfavorable weather, of every brief break or opening that would enable a pilot to get through. Accuracy

and promptness are the main essentials of such a service. Let us see what kind of an organization can best provide them.

Accuracy. In the first place, there must, of course, be a system of regular weather reports at least twice, preferably four times, a day from a large area. This system of reports is fundamental, and all civilized countries have it for their own areas and usually for portions of adjoining countries and oceans. The reports are based upon observations made by trained personnel, with standard instrumental equipment and include upper air as well as surface conditions. They are collected at certain central points, and weather maps, bulletins, and forecasts are issued.

The next requirement is a system of supplementary reports for comparatively small areas, each area covering a section of an airway. As yet it is difficult to say how frequent these reports should be, but it is significant that those who have had most experience in this work strongly advocate at least 2-hourly and preferably hourly reports. If at 2- or 3-hourly intervals, they should include not only places on the airway itself but also a few selected points at some distance from and on both sides of it. These enable the meteorologist to watch the development and movement of adverse conditions approaching the airway from either side. If the reports are made once each hour, they may be limited to points on the airway itself, except that every second or third one should include also those at some distance from it.

These intermediate reports are based upon observations made by properly instructed, though not technically trained, personnel and with instruments for indicating only the more important elements. The reports are accurate, but not of the high precision required in the general system for the whole country, and they include only information that is really needed, such as the state of the weather, ceiling, visibility, wind direction and velocity, temperature, pressure, and a statement

of any unfavorable condition, such as a thunderstorm, deep snow on ground, etc.

Promptness. So much for the character of the data, or to express it in another way, the accuracy of the service. No matter how accurate, the service will fall down unless it is also prompt. Promptness requires: (a) an adequate system of communications; (b) close contact between meteorologist and pilot.

Communications. Naturally, the prompt collection of these reports requires a very efficient communications system, the organization of which is a function of the Airways Division of the Department of Commerce. It was found very early that, for this particular purpose, dependence cannot be placed on the ordinary commercial facilities. During the times of peak loads, that is, in the middle of the day, absolute promptness could not be guaranteed. All types of business are entitled to equal service. It was evident, therefore, that a system of communications under absolute control is necessary. This has been accomplished on some of the main airways through the installation of a printing telegraph or "teletype" circuit. The circuits consist of leased telephone lines 500 to 800 miles (800 to 1,300 km.) in length between terminal airports with drops at the intermediate weather reporting stations, each one of which has an automatic typewriter or teletype machine. The messages are typed on these machines in sequence, the various stations following one another in rapid succession, and each message is received on tape by all other stations in the circuit. This system of communications is prompt and is rapidly increasing in efficiency and reliability. The Department of Commerce plans to extend it eventually to all Interstate Trade Air Routes.

Contact. The other requirement for prompt service—that of close contact with the pilot—is one that the meteorologist must provide. Experience during the past few years is con-

clusive on this point, to the extent in fact that the assignment of competent meteorologists to a central airport at the more important airway terminals is now the established policy of the Weather Bureau. Some cities have many separate airports and in those cases a closely interlocking communications system should be arranged and will undoubtedly be developed whereby the meteorologist will be kept in close touch with all of them, each receiving the reports and forecasts for routes of which it is one of the termini.

Before each flight the pilot wants answers to the following questions:

1. What is the weather now at his terminal?
2. What is the weather now along his route?
3. Will there be any change during the next 1 to 4 hours (this period depending upon the length of the flight) and, if so, what kind of a change?

Answers to the first two questions are provided by a fast and dependable system of communications. Answer to the third is given by the trained meteorologist at the airport, where he can see and study the reports "hot off the wire," make his forecasts and talk the situation over with the pilot. Thus promptness and accuracy are combined in a service that results in a minimum of delayed and canceled flights.

The service is still incomplete, however. There are and always will be, at least for a long time to come, many occasions when the weather outlook is decidedly uncertain even to the best-trained meteorologist. And this is where the value of a ground-to-plane communications system is shown. The pilot starts out with good weather prevailing and expected, but a fog suddenly develops at his terminal. A radio message tells him so and instructs him to turn back or land at the nearest field to his destination. Thus, within the limits of human endeavor, flying is made safe as well as efficient.

Summary. Such, in brief, are the essential features of weather service for aeronautics. Although we should guard against anything like dogmatic assertion regarding the requirements and possibilities of the future, which will, of course, bring marked changes in design and construction of aircraft and in navigational aids, including radio range beacons, television, and the radio altimeter among others, it seems safe nevertheless to say that there will always be need for weather service essentially as described in this Chapter. It is significant that the organization of such service is along these lines in all countries. Details of organization differ and in some measure will always differ, but the basic features are the same. This intensive type of service is being extended to all land areas as the needs develop. Not only so; recently, arrangements have been worked out at international meetings whereby numerous reports from ships at sea will be radioed to designated centers and there used as a basis for bulletins and forecasts covering different parts of the oceans. As this system is perfected, such bulletins will be available at frequent intervals for all areas in which there is any traffic, either marine or aerial, and therefore from which reports can be received.

APPENDIX

APPENDIX 1

QUESTIONS

In the following questions, no pretense is made that they cover the entire subject. However, they are representative of the type of questions and topics that may well be presented to students.

Introduction

1. What are the chief constituents of the atmosphere?
2. Give the average percentage occurrence of water vapor.
3. Is the atmosphere a mechanical mixture or a chemical compound?
4. Name the principal meteorological elements.
5. Distinguish between weather and climate.
6. Define meteorology, aerology, and aeronautical meteorology.

Chapter 1. General Circulation of the Atmosphere

1. Discuss the principal influences in the temperature distribution over the globe.

2. What are the chief features shown in isothermal charts of the world for July and January?

3. Explain the relation between temperature distribution and pressure distribution.

4. What effect does the earth's rotation have on air movement?

5. Name and describe the four chief belts or systems of pressure and wind, comprising the "general circulation."

6. Where are monsoons best developed?

7. Discuss briefly land and sea breezes, mountain and valley winds, and chinook or foehn.

Chapter 2. Instruments and Methods of Observation

1. What meteorological elements are observed chiefly with instruments? Without instruments?

2. What is the Beaufort scale? Of how many numbers does it consist?

3. What are the principal meteorological elements concerning which information is needed for flying activities?

4. Briefly describe the instrumental and other apparatus used in making observations of these elements.

Chapter 3. Vertical Structure of the Atmosphere

1. Define troposphere; stratosphere; tropopause.
2. Discuss the cause of temperature decrease with altitude.
3. Define adiabatic rate; lapse rate.
4. What effect does moisture have on temperature decrease with altitude?
5. Give the average rate of temperature decrease, for all conditions, in the lower half of the troposphere.
6. What change occurs with altitude in the diurnal range of temperature?
7. Distinguish between absolute and relative humidity. Define vapor pressure; dew-point.
8. What is the hypsometric equation?
9. Discuss the effect of temperature on pressure decrease with altitude.
10. What is the relation of atmospheric density to pressure, temperature, and moisture?
11. What is the approximate level of constant density?
12. Define Toussaint's "standard atmosphere." How does it compare with average conditions in the United States?
13. For what is the standard atmosphere chiefly used?

Chapter 4. Winds

1. Why do not winds at the surface blow parallel to the isobars?
2. What are the characteristic features of the turning of winds with altitude?
3. What is meant by "gradient" wind? At what average altitude is it found?
4. Discuss the change in velocity with altitude, as related to wind direction at the surface.
5. Discuss the characteristic annual variation; diurnal variation.
6. What are the two chief types of turbulence?
7. At what levels is turbulence most pronounced?
8. Discuss the effects of buildings and different types of terrain on turbulence.
9. What are the chief dangers of turbulent conditions to aircraft in flight?

10. Summarize briefly the conditions favorable for soaring flight.

11. Indicate diagrammatically the use that can be made of reports of wind direction and velocity in plotting a course.

12. Discuss the significance of resultant winds and data concerning the frequency of winds of different directions and velocities in determining flight schedules.

13. What are the chief characteristics of resultant winds at flying levels in the United States?

14. Is there any basis of fact to statements occasionally made that, "if you go high enough, you will have a trade wind of enormous velocity"?

Chapter 5. Fog

1. What are the principal causes of fog formation?

2. What is the usual character of the temperature lapse rate during dense fogs?

3. Why are fogs more frequent in winter than in summer over inland areas?

4. What are the chief characteristics of radiation fogs? Advection fogs?

5. What effect does mixing have in the formation of fog?

6. What is mountain fog?

7. Give a brief statement regarding the height of fog. Also, the duration of fog.

8. Is artificial dispersion of fog possible? With methods thus far developed is it practicable?

9. Discuss the distribution of fog in the United States.

10. What are the regions of greatest fog frequency in summer?

Chapter 6. Clouds

1. What are the chief differences between fogs and clouds?

2. Give the international classification of clouds.

3. Briefly describe each of the 10 main types, including their general characteristics as to height and thickness.

4. What cloud has the greatest thickness?

5. As a rule, what controls the speed of cloud movement?

6. Do clouds float? Explain why they appear to do so.

7. Explain the formation of rain.

8. Indicate briefly the distribution of cloudiness in the United States.

9. In what part of the day and year do maximum and minimum cloudiness occur?

Chapter 7. Ceiling and Visibility

1. What is understood by ceiling?
2. How is ceiling related to topography?
3. In what part of the day and year are ceilings highest and lowest respectively?
4. Define visibility.
5. How is horizontal visibility observed?
6. What is the characteristic diurnal and annual variation of horizontal visibility?
7. Discuss the relations between horizontal visibility and smoke and dust, convection, wind velocity, humidity, and type of pressure.
8. Does good horizontal visibility necessarily mean good vertical visibility?
9. Describe the "dust horizon."
10. State the relations between vertical visibility and humidity, wind velocity and convection.
11. Write brief summaries of ceiling and visibility characteristics in different sections of the United States.

Chapter 8. Thunderstorms

1. Name the two principal types of thunderstorms.
2. What is the underlying cause of all thunderstorms?
3. Describe the vertical movements in thunderstorms.
4. Discuss briefly the wind gust, squall cloud, storm collar, mammato-cumulus.
5. Explain the formation of lightning; of hail.
6. Discuss the annual, diurnal and geographic distribution of thunderstorms in the United States.
7. State briefly what is known concerning the height, duration, direction and rate ot movement and size of thunderstorms in the United States.
8. Describe the three chief dangers that thunderstorms offer to flying.
9. What precautions should be taken in flying during conditions favorable for thunderstorms?
10. In what section of low-pressure areas are tornadoes most likely to form?
11. What are the chief features of tornadoes?

Chapter 9. Cyclones and Anticyclones

1. State Buys-Ballots' Law.
2. Describe the chief characteristics of cyclones.
3. What is a secondary Low and how is it formed?
4. Discuss cyclones as to size, types in the United States, and direction and rate of movement.
5. In what respects do tropical cyclones differ from extratropical?
6. Describe the chief characteristics of anticyclones as to accompanying weather, size, types in the United States, frequency, and direction and rate of movement.
7. Discuss the movements of both cyclones and anticyclones, as related to the upper winds.
8. What is the characteristic distribution of upper air temperature in cyclones and anticyclones?
9. What is the effect of this distribution on the pressure distribution in the upper levels?
10. Where are upper winds normally strongest in cyclones and anticyclones?
11. Why does the source of the air have an opposite relation to the temperature in the stratosphere from that in the troposphere?

Chapter 10. Weather Forecasting

1. Describe the chief steps in the preparation of the daily weather map.
2. For how long a period in advance are the general forecasts usually issued?
3. Discuss the polar front theory.
4. What is meant by discontinuity?
5. How is an occlusion formed?
6. What are the main features of the line squall?
7. What precautions should be observed in flying during line squall conditions?

Chapter 11. Airship Meteorology

1. What are the three chief conditions of wind affecting the handling of airships on the ground?
2. Discuss the chief characteristics of each of these three conditions.
3. What is known concerning the vertical extent of wind shifts?
4. Of what special significance are sharp discontinuity boundaries to airship operation?

5. How may advantage be taken of the diurnal variation in wind velocity, in connection with docking and mooring?

6. Of what use are data concerning temperature in connection with airship operation?

7. Discuss the effect of steep lapse rates and inversions on airship operation.

8. Define superheat.

9. To what meteorological elements should consideration be chiefly given in making a survey of sites for an airship base?

10. In what chief respect does forecasting weather for airships differ from general forecasting?

11. How can advantage be taken of the weather map and of forecasts based thereon to make a successful flight to one's destination when bad conditions prevail on the direct route?

Chapter 12. North Atlantic and Arctic Meteorology

1. Summarize the weather and wind conditions in temperate latitudes over the north Atlantic.

2. Of what special significance is temperature so far as flight across the Atlantic is concerned?

3. What is known as to the height of fogs over the Atlantic?

4. What are the probable wind conditions at flying levels, on the average?

5. How do conditions compare for eastward and westward flight, so far as winds are concerned?

6. What seem to be the chief requirements for successful trans-atlantic flying on a more or less regular schedule?

7. Discuss wind and weather conditions in the Arctic.

8. What do records show as to storminess in that region?

9. What is the characteristic relation of temperature to altitude in the Arctic?

10. In general, how do conditions in the Arctic compare with those in the North Atlantic, so far as flying on regular schedule is concerned.

Chapter 13. Ice Formation on Aircraft

1. Discuss the relative effects of ice formation on airships, free balloons, and airplanes.

2. What are the four most serious effects on airplanes?

3. What are the weather conditions most favorable for ice formation?

4. What courses are open to a pilot when ice conditions are present?

5. What is the one significant point on the thermometer, so far as ice danger is concerned?

6. Discuss the geographic and seasonal relations to ice formation in the United States.

7. What pressure distribution is most favorable for ice formation?

Chapter 14. Airways Weather Service

1. In what two principal ways does meteorology aid aeronautics?

2. Discuss the use that can be made of statistical data in selecting an airport site; in determining flight schedules.

3. What are the chief requirements of weather service to provide for the safety and efficiency of flying activities?

APPENDIX 2

DISTRIBUTION OF WEATHER REPORTS AND FORECASTS BY RADIO

Chief broadcasting agencies. Radio weather broadcasts for general public information are made by the Department of Commerce, the Navy Department, and by numerous commercial companies. In all cases, the reports and forecasts included in these broadcasts are furnished by the Weather Bureau.

Airways broadcasts. As stated in Chapters 10 and 14, the Department of Commerce is charged with the duty of providing suitable communication facilities for commercial airways. Included in its program is a network of radio stations which eventually will cover the entire country. These stations are located at or very close to important terminal airports at intervals of approximately 200 to 300 miles (300 to 500 km.).

Although designed primarily to give information to aircraft in flight, the information broadcast is equally available to any one on the ground possessing a suitable receiving set. The broadcasts are made by radiophone on frequencies ranging from 285 to 350 kilocycles. Adjacent stations are allocated at least 12 to 18 kilocycles apart to avoid interference. Aircraft equipped with proper receiving sets are able to pick up these reports at distances up to 150 miles (250 km.). On the ground they can be received 250 to 300 miles (400 to 500 km.).

The broadcasts include the information outlined in Chapter 14, viz., hourly reports of conditions along the airways radiating from the broadcasting centers; short range forecasts, covering periods of 2 to 4 or 5 hours; and longer period forecasts at proper intervals. In addition, these stations send out beacon signals, during periods between the weather broadcasts, which enable pilots to keep on a straight course, even when the ground is hidden by fog or impaired visibility from other causes.

Information as to the locations of broadcasting stations, their frequencies, etc., can be obtained from the Weather Bureau or the Department of Commerce, Washington, D. C.

Aviation and commercial broadcasts. Radio broadcasts of information of value to aviation and commercial interests are made twice daily by the Weather Bureau through the U. S. Naval radio stations located at Washington, D. C. (Arlington NAA), and San Francisco, Cal., NPG. The broadcasts from San Francisco, Cal. are made at 6:18 A.M. and 6:18 P.M., local or 120th meridian time, while the broadcasts from Washington are made at 8:05 A.M. and 8:05 P.M., local, or 75th meridian time.

The frequencies used at NPG, San Francisco, Cal., are 8,590, 108, and 42.8 kilocycles (34.9, 2,776, and 7,000 m., respectively). Those used at NAA, Washington, D. C., are 4,015, 8,030, and 13,305 kilocycles (74.7, 37.4, and 22.53 m., respectively) for the 8:05 A.M. broadcasts, and 4,015 kilocycles only (74.7 m.) in the 8:05 P.M. broadcast.

The broadcasts, made direct from the Weather Bureau offices at both places, are quite uniform, and consist of the following. Regular Weather Bureau weather observations made at 8 A.M. and 8 P.M., 75th meridian time, at about 200 stations in the United States, Canada, and Alaska. These are in the regular Weather Bureau word code and contain information as follows: sea-level barometric pressure and current temperature; wind direction, state of weather, and temperature; wind velocity and amount of precipitation; rise or fall in pressure; thunderstorms; clouds; etc.

Aerological, or pilot balloon upper-air, observations made at certain Weather Bureau stations, follow the coded weather observations. These reports are based on readings which give the wind velocity and direction at the surface, and the following levels aloft: 250 meters, 500 meters, 1,000 meters, 1,500 meters, 2,000 meters, 3,000 meters, and 4,000 meters, and for the maximum altitude observed. Data for visibility and clouds are also included in this broadcast. These observations are coded in the Weather Bureau Aerological Code.

The broadcast from San Francisco also includes a selected list of vessel weather observations taken in the eastern Pacific

Ocean which enable aviation interests to know the conditions at sea. These reports are in the Vessel Weather Code of the Weather Bureau. They consist of the position of vessels, sea-level barometric pressure, current temperature, wind direction, state of weather, and wind velocity.

The foregoing broadcasts are described in the Weather Bureau radio circulars Nos. 16 (Washington) and 17 (San Francisco). These are revised from time to time, as occasion demands, in order that information regarding changes in wave lengths, etc., may be kept accurate and up to date.

Additional major bulletin broadcasts of general interest to marine interests are made from San Francisco and Washington. However, these bulletins may be of service to aviation interests, especially in connection with transoceanic flights.

The major marine bulletin broadcast from NAA, at Washington, D. C., is sent twice daily, throughout the year, at 10 A.M. and 10 P.M., local, or 75th meridian time. It is broadcast on frequencies of 68, 113, and 16,120 kilocycles (4,409, 2,653, and 18.6 m., respectively) at 10 A.M., and on 68 and 113 kilocycles (4,409 and 2,653 m., respectively) at 10 P.M.

The bulletin consists of coded reports from many stations, ship reports from the Atlantic, Gulf and Caribbean waters, weather summaries, forecasts, and storm warnings.

The bulletin broadcast from NPG at San Francisco, Cal., is similar in scope except that it is broadcast on frequencies of 42.8, 108, and 8,590 kilocycles (7,000, 2,776, and 34.9 m., respectively) at 7:30 A.M. and 7:30 P.M., local, or 120th meridian time.

This broadcast also includes flying weather forecasts for aviation zones 12, 13, and 14 (see Figure 63, Chapter 10) and regular forecasts for the states of Washington, Oregon, Idaho, Nevada, and California, immediately following the first part, or coded portion of the bulletin.

The foregoing broadcasts are described in Weather Bureau radio circulars Nos. 10 (San Francisco) and 13 (Washington).

In addition to the distribution of weather reports and forecasts made through Government radio stations, a large number of commercial companies throughout the country are cooperating with the Weather Bureau in broadcasting similar information by both

radio telegraph and radiophone. Those by radio telegraph are issued, as a rule, for the benefit of private interests but are available to any others having suitable sets and trained operators for receiving them. The character of the broadcasts varies according to the needs of the regions concerned. Thus, there is a special service for the benefit of navigation on the Great Lakes, another for the Gulf of Mexico and the Caribbean Sea, and others for the Atlantic and Pacific coasts.

Finally, there is the purely local distribution of state and local forecasts by radiophone by about 250 of the principal broadcasting stations in all parts of the country. There is no resident of any state having a reasonably modern receiving set who cannot obtain forecasts applying to his locality if he wishes to do so. The schedules, wave-lengths, etc., of these radio stations are still subject to more or less change, so that a list now effective would soon be out of date. It is an easy matter, however, at any time to obtain information on these points by merely communicating with Weather Bureau stations having supervision of forecast distributions in the various states. A list of Weather Bureau stations in the United States is given in Appendix 3. Those marked with an asterisk (*) have supervision of forecast distribution by radio in their respective states.

APPENDIX 3

WEATHER BUREAU STATIONS

The following list contains all first-order stations of the Weather Bureau, as of July, 1930. These constitute the Bureau's primary network and furnish service for all sorts of activities—agriculture, commerce, and navigation. No changes of consequence are likely to be made in this list, except that, from time to time, there will be additions to the number of airport stations.

The Weather Bureau has also what may be called a secondary network, comprising a large number of stations that make special observations for various branches of the service, including, in 1930, some 300 for airways service. Because of frequent changes (principally additions) in their number and locations, a list is not given here, but information regarding them can be obtained at any time from the U. S. Weather Bureau, Washington, D. C.

Weather Bureau Stations in the United States

Forecast centers in bold-faced type. *Climatological section center. †Aerological station. ‖Also pilot balloon observations. ‡Airways service at airport. §Fruit-frost service only.

Abilene, Tex.
Albany, N. Y.‖‡
Albuquerque, N. Mex.‖
Alpena, Mich.
Amarillo, Tex.
Anniston, Ala.
Apalachicola, Fla.
Asheville, N. C.
Atlanta, Ga.*‖‡
Atlantic City, N. J.
Augusta, Ga.
Austin, Tex.

Baker, Ore.
Bakersfield, Cal.‡
Baltimore, Md.*
Bellefonte, Pa.‖‡
Binghamton, N. Y.
Birmingham, Ala.
Bismarck, N. Dak.*
Block Island, R. I.
Boise, Idaho*‖
Boston, Mass.*‖‡
Broken Arrow, Okla.†‖
Brownsville, Tex.‖‡
Buffalo, N. Y.‖‡
Burlington, Vt.‖

Cairo, Ill.
Canton, N. Y.
Cape Henry, Va.
Charles City, Iowa
Charleston, S. C.
Charlotte, N. C.
Chattanooga, Tenn.
Cheyenne, Wyo.*‖‡
Chicago, Ill.‖‡
Cincinnati, Ohio‖‡
Cleveland, Ohio‖‡
Columbia, Mo.*
Columbia, S. C.*
Columbus, Ohio*‡
Concord, N. H.
Concordia, Kans.
Corpus Christi, Tex.

Dallas, Tex.‖‡
Davenport, Iowa‖‡
Dayton, Ohio
Del Rio, Tex.‖
Denver, Colo.*‖
Des Moines, Iowa*
Detroit, Mich.‖‡
Devils Lake, N. Dak.
Dodge City, Kans.
Dubuque, Iowa
Due West, S. C.†‖
Duluth, Minn.

Eastport, Me.

Elkins, W. Va.
Ellendale, N. Dak.†||
El Paso, Tex.
Erie, Pa.
Escanaba, Mich.
Eureka, Cal.
Evansville, Ind.||‡

Fairbanks, Alaska||
Fort Smith, Ark.
Fort Wayne, Ind.
Fort Worth, Tex.
Fresno, Cal.||‡

Galveston, Tex.
Grand Haven, Mich.
Grand Junction, Colo.
Grand Rapids, Mich.
Green Bay, Wis.
Greensboro, N. C.||‡
Greenville, S. C.
Groesbeck, Tex.†||

Hannibal, Mo.
Harrisburg, Pa.
Hartford, Conn.
Hatteras, N. C.
Havre, Mont.||
Helena, Mont.*
Honolulu, Hawaii*
Houghton, Mich.
Houston, Tex.*
Huron, S. Dak.*

Indianapolis, Ind.*‡
Iola, Kans.
Ithaca, N. Y.*

Jacksonville, Fla.*||‡
Juneau, Alaska*

Kalispell, Mont.
Kansas City, Mo.||‡
Keokuk, Iowa
Key West, Fla.||
Knoxville, Tenn.||

La Crosse, Wis.
Lander, Wyo.
Lansing, Mich.*
Lewiston, Idaho
Lexington, Ky.
Lincoln, Neb.*
Little Rock, Ark.*
Los Angeles, Cal.||‡
Louisville, Ky.*‡
Ludington, Mich.
Lynchburg, Va.

Macon, Ga.
Madison, Wis.
Marquette, Mich.
Medford, Ore.||‡
Memphis, Tenn.||
Meridian, Miss.
Miami, Fla.‡
Miles City, Mont.
Milwaukee, Wis.*
Minneapolis, Minn.*
Mobile, Ala.
Modena, Utah||
Montgomery, Ala.*
Moorhead, Minn.

Nantucket, Mass.
Nashville, Tenn.*
New Haven, Conn.
New Orleans, La.*||
New York, N. Y.||‡
Nome, Alaska||
Norfolk, Va.
Northfield, Vt.
North Head, Wash.
(P. O. Ilwaco, Wash.)
North Platte, Neb.||‡

Oklahoma City, Okla.*||
Omaha, Neb.||‡
Oswego, N. Y.

Palestine, Tex.
Parkersburg, W. Va.*
Pensacola, Fla.
Peoria, Ill.
Philadelphia, Pa.*
Phoenix, Ariz.*||
Pierre, S. Dak.
Pittsburgh, Pa.
Pocatello, Idaho
Pomona, Cal.§
Port Angeles, Wash.
Port Arthur, Tex.
Port Huron, Mich.
Portland, Me.
Portland, Ore.*||‡
Providence, R. I.
Pueblo, Colo.

Raleigh, N. C.*
Rapid City, S. Dak.
Reading, Pa.
Red Bluff, Cal.
Redding, Cal.||‡
Reno, Nev.*||‡
Richmond, Va.*‡
Rochester, N. Y.
Roseburg, Ore.
Roswell, N. Mex.
Royal Center, Ind.†||

Sacramento, Cal.
St. Joseph, Mo.
St. Louis, Mo.||‡
St. Paul, Minn.||‡
Salt Lake City, Utah*||‡
San Antonio, Tex.
San Diego, Cal.‡
Sandusky, Ohio
Sandy Hook, N. J.
(P. O. Fort. Hancock, N. J.)
San Francisco, Cal.*||‡
San Jose, Cal.
San Juan, P. R., W. I.*||
Santa Fe, N. Mex.*
Sault Sainte Marie, Mich.||
Savannah, Ga.
Scranton, Pa.
Seattle, Wash.*||‡
Sheridan, Wyo.||
Shreveport, La.
Sioux City, Iowa
Spokane, Wash.||
Springfield, Ill.*‡
Springfield, Mo.
Syracuse, N. Y.‡

Tacoma, Wash.
Tampa, Fla.
Tatoosh Island, Wash.
Taylor, Tex.
Terre Haute, Ind.
Thomasville, Ga.

Topeka, Kans.*
Trenton, N. J.*
Valentine, Neb.
Vicksburg, Miss.*
Walla Walla, Wash.
Washington, D. C.||‡
Wausau, Wis.
Wichita, Kans.||‡
Williston, N. Dak.
Wilmington, N. C.
Winnemucca, Nev.
Wytheville, Va.
Yakima, Wash.||
Yankton, S. Dak.
Yellowstone Park, Wyo
Yuma, Ariz.

Weather Bureau Airport Stations in the United States

Albany, N. Y.
Atlanta, Ga.
Bakersfield, Cal.
Bellefonte, Pa.
Bolling Field, D. C. (P. O. Anacostia, D. C.)
Brownsville, Tex.
Buffalo, N. Y.
Chattanooga, Tenn.
Cheyenne, Wyo.
Chicago, Ill.
Cincinnati, Ohio
Cleveland, Ohio
Columbus, Ohio
Dallas, Tex.
Detroit, Mich.
East Boston, Mass.
Elko, Nev.
Evansville, Ind.
Fort Crook, Neb. (Omaha)
Fresno, Cal.
Glendale, Cal. (Los Angeles)
Greensboro, N. C.
Houston, Tex.
Indianapolis, Ind.
Jacksonville, Fla.
Kansas City, Mo.
Louisville, Ky.
Medford, Ore.
Miami, Fla.
Moline, Ill.
Murfreesboro, Tenn. (Nashville)
New Brunswick, N. J. (New York)
North Platte, Neb.
Oakland, Cal.
Pasco, Wash.
Portland, Ore.
Redding, Cal.
Reno, Nev.
Richmond, Va.
Robertson, Mo. (St. Louis)
St. Paul, Minn.
Salt Lake City, Utah
San Diego, Cal.
Seattle, Wash.
Spartanburg, S. C.
Springfield, Ill.
Syracuse, N. Y.
Toledo, Ohio
Tulsa, Okla.
Wichita, Kans.

APPENDIX 4

METEOROLOGICAL SERVICES OF THE WORLD

The following list gives the addresses of headquarters or central offices of the official meteorological services of the world and a few leading independent meteorological observatories. They are given in alphabetical order of the countries concerned, except that those for Africa and the West Indies are in groups for those regions as a whole.

Service Météorologique d'Algérie, l'Université, Algiers, **Algeria.**
Meteorological Observatory, Sao Paulo de Loando, **Angola**, Africa.
Controller, Physical Department, Dawawyn Post Office, Cairo, **Egypt.**
Observ. Campos Ridrigues, P. O. Box 256, Lourenço Marques, **Portuguese East Africa.**
Observatoire Royal, Tananarivo, **Madagascar.**
Observatory, Bulawayo, **Rhodesia**, South Africa.
Chief Meteorologist, Dept. Irrigation, P. O. Box 309, Pretoria, **South Africa.**
Osservatorio, Meteorologico, **Tripoli,** Libya, Africa.
Director General, Service Météorologique, **Tunis,** Africa.
Dirección de Meteorología, Paseo Colon 974, Buenos Aires, **Argentina.**
Commonwealth Bureau of Meteorology, Melbourne, **Australia.**
Zentralanstalt für Meteorologie und Geodynamik, Hohe Warte 38, Vienna, **Austria.**
Serviço Meteorológico dos Açôres, Ponta Delgada, **Azores.**
Institut Royal Météorologique, Uccle, **Belgium.**
Directoria de Meteorologia, Palacio dos Estados, 4.0 andar, Rio de Janeiro, **Brazil.**
Director, Meteorological Service, Toronto, **Canada.**
Surveyor-General, Colombo, **Ceylon.**
Oficina Meteorológica, Casilla, 717, Santiago, **Chile.**
Royal Observatory, Hongkong, **China.**
Meteorological Observatory, Tsingtau, **China.**
Observatoire Météorologique, Zi-ka-wei, near Shanghai, **China.**
Observatoire Central Météorologique, Phu-Lien near Haiphong, Tonkin, **Indo-China.**
Observatorio S. Bartolomé, Apartado 270, Bogota, **Colombia.**
Meteorological Institute, Prague, II U Karlova, **Czechoslovakia.**

Meteorologisk Institut, Copenhagen, **Denmark.**

Meteorological Office, Air Ministry, Kingsway, London, W. C. 2, **England.**

Valtion Meteorologinen Keskuslaitos, Helsingfors, **Finland.**

Office National Météorologique. 176 Rue de l'Université, Paris VII, **France.**

Institut de Physique du Globe, 38, Boulevard d'Anvers, Strasbourg, **France.**

Meteorologisches Observatorium, Aachen, **Germany.**

Aeronautisches Observatorium, Lindenberg, Kr. Beeskow, **Germany.**

Preussisches Meteorologisches Institut, Schinkelplatz 6, Berlin W., **Germany.**

Hessisches Landesamt für Wetter und Gewässerkunde, Darmstadt, **Germany.**

Landes-Wetterwarte, Grosse Meissnerstr, 15, Dresden N 6, **Germany.**

Deutsche Seewarte, Hamburg, **Germany.**

Badische Landeswetterwarte, Durlacher Alle 56, Karlsruhe, **Germany.**

B. Landeswetterwarte, Gabelbergerstr. 55/1, Munich, **Germany.**

Württemberg Statist. Landesamt, Meteorol. Abt., Stuttgart, **Germany.**

Drachenstation, Friederichshafen, Württemberg, **Germany.**

Observatoire National, Athens, **Greece.**

Royal Meteorological and Magnetical Institute, Budapest, **Hungary.**

Loggildingarstofan, Reykjavik, **Iceland.**

Alipore Observatory, Calcutta, **India.**

Indian Meteorological Dept., Poona, 5, **India.**

Osserv. Geodinamico e Aerologico, Pavia, **Italy.**

R. Ufficio Centrale di Meteorologia e Geodinamica, Rome, **Italy.**

Central Meteorological Observatory, Tokyo, **Japan.**

K. Magnetisch en Meteorologisch Observatorium, Batavia, **Java.**

Meteorological Bureau, Department of Agriculture, Todlebena Pulvari No. 6, Riga, **Latvia.**

Royal Alfred Observatory, Pamplemousses, **Mauritius.**

Weather Bureau, Office of the Civil Commissioner, Baghdad, **Mesopotamia.**

Observatorio Meteorológico Central, Tacubaya, D. F., **Mexico.**

K. Nederl. Meteorol. Inst., De Bilt near Utrecht, **Netherlands.**

Meteorological Office, Wellington, **New Zealand.**

Geofysisk Institut, Avd B, Bergen, **Norway.**

Meteorologisches Institut, Christiania, **Norway.**

Philippine Weather Bureau, Manila, **P. I.**

Inst. Météorologique de Pologne, Rue Nowy Swiat, Warsaw, **Poland.**

Observatorio Infante D. Luiz, Lisbon, **Portugal.**

Institutul Meteorologic Central, Bucuresti, **Roumania.**

Observatoire Géophysique Central, Leningrad, **Russia.**

Ukrainian Meteorological Service, Sofiskaya 18, Kiev, Ukrainia, **Russia.**

Samoa Observatory, Apia, **Samoa.**

Observatoire Central, Belgrade, **Serbia.**

Servei Meteorologic de Catalunya, C. Urgell 187, Barcelona, **Spain.**

Obs. Central Meteorológico, Apartado 385, Madrid, **Spain.**

Observatorio del Ebro, Tortosa, **Spain.**

Statens Meteorologisk Hydrografiska Anstalt, Stockholm, **Sweden.**

Schweiz. Meteorologische Centralanstalt, Zürich, **Switzerland.**

Observatoire de Ksara, Saïd-Nail près Beirut **Syria.**

Service Météorologique, Ministere des Travaux Publics Ankara (Angora), **Turkey.**

U. S. Weather Bureau, Washington, D. C., **U.S.A.**

Blue Hill Observatory, Hyde Park, Mass., **U.S.A.**

Inst. Meteorológico Nacional, Montevideo, **Uruguay.**

Observatorio Cagigal, Caracas, **Venezuela.**

Observatorio Nacional, Casa Blanca, Havana, **Cuba, W.I.**

Oficina Meteorológica, Duarte 33, San Pedro de Marcoris, **Dominican Republic, W.I.**

Observatoire St. Martial, Port-au-Prince, **Haiti, W.I.**

Government Meteorologist, Montego Bay, **Jamaica, W.I.**

APPENDIX 5

BIBLIOGRAPHY

The following list is, of course, very far from complete. It includes the better known general treatises on meteorology, and in addition, such books and papers as are believed to be of most interest and value in aeronautics. Numerous other papers containing the results of aerological research have been published in the *Monthly Weather Review* and in many cases a limited supply of reprints is available. A list of these, and copies as long as the supply lasts, will be furnished on application to the Chief of the Weather Bureau, Washington, D. C.

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APPENDIX 6

CONSTANTS AND CONVERSION FACTORS AND TABLES

Constants

Gravity acceleration	$=980.665$ cm./sec.^{2}
Gram weight	$=980.665$ dynes
Atmospheric pressure	$=1{,}013{,}250.144+$ dynes per cm.^{2}; that is, the pressure of a mercury column at standard gravity and 0° C. 760 millimeters high
Bar(meteorological)	$=1{,}000{,}000$ dynes per square centimeter

Densities (grams per cu. cm.)

Mercury at 0° C.	$=13.5951$
Air, dry, containing normal amount of CO_2 at standard atmospheric pressure and 0° C.	$=0.0012930$
Weight of standard dry air	$=1.2930$ kg./m.^{3}
	1.29152 oz./ft.^{3}
	0.08072 lb./ft.^{3}

Conversion Factors and Tables

Detailed tables may be found in "Smithsonian Meteorological Tables," (4th rev. ed.), 1918. There follow a few of those that are most generally used, together with the conversion factors. The tables cover a range such that any conversion needed in ordinary work may be made either directly or by a change in the decimal point. For example, in the pressure conversion table, 29.2 inches = 741.7 millimeters. (This rule does not apply to the temperature table.)

Pressure

1 inch	$=25.40005$ millimeters
	$=33.86395$ millibars

1 millimeter = 0.03937 inch
= 1.33322 millibars

1 millibar = 0.02953 inch
= 0.75006 millimeter

TABLE 22. INCHES INTO MILLIMETERS AND MILLIBARS

Inches	Millimeters					Millibars				
	0.00	0.02	0.04	0.06	0.08	0.00	0.02	0.04	0.06	0.08
0.0	0.00	0.51	1.02	1.52	2.03	0.00	0.68	1.35	2.03	2.71
0.1	2.54	3.05	3.56	4.06	4.57	3.39	4.06	4.74	5.42	6.10
0.2	5.08	5.59	6.10	6.60	7.11	6.77	7.45	8.13	8.80	9.48
0.3	7.62	8.13	8.64	9.14	9.65	10.16	10.84	11.51	12.19	12.87
0.4	10.16	10.67	11.18	11.68	12.19	13.55	14.22	14.90	15.58	16.25
0.5	12.70	13.21	13.72	14.22	14.73	16.93	17.61	18.29	18.96	19.64
0.6	15.24	15.75	16.26	16.76	17.27	20.32	21.00	21.67	22.35	23.03
0.7	17.78	18.29	18.80	19.30	19.81	23.70	24.38	25.06	25.74	26.41
0.8	20.32	20.83	21.34	21.84	22.35	27.09	27.77	28.45	29.12	29.80
0.9	22.86	23.37	23.88	24.38	24.89	30.48	31.15	31.83	32.51	33.19
1.0	25.40	25.91	26.42	26.92	27.43	33.86	34.54	35.22	35.90	36.57
1.1	27.94	28.45	28.96	29.46	29.97	37.25	37.93	38.60	39.28	39.96
1.2	30.48	30.99	31.50	32.00	32.51	40.64	41.31	41.99	42.67	43.35
1.3	33.02	33.53	34.04	34.54	35.05	44.02	44.70	45.38	46.05	46.73
1.4	35.56	36.07	36.58	37.08	37.59	47.41	48.09	48.76	49.44	50.12
1.5	38.10	38.61	39.12	39.62	40.13	50.80	51.47	52.15	52.83	53.51
1.6	40.64	41.15	41.66	42.16	42.67	54.18	54.86	55.54	56.21	56.89
1.7	43.18	43.69	44.20	44.70	45.21	57.57	58.25	58.92	59.60	60.28
1.8	45.72	46.23	46.74	47.24	47.75	60.96	61.63	62.31	62.99	63.66
1.9	48.26	48.77	49.28	49.78	50.29	64.34	65.02	65.70	66.37	67.05
2.0	50.80	51.31	51.82	52.32	52.83	67.73	68.41	69.08	69.76	70.44
2.1	53.34	53.85	54.36	54.86	55.37	71.11	71.79	72.47	73.15	73.82
2.2	55.88	56.39	56.90	57.40	57.91	74.50	75.18	75.86	76.53	77.21
2.3	58.42	58.93	59.44	59.94	60.45	77.89	78.56	79.24	79.92	80.60
2.4	60.96	61.47	61.98	62.48	62.99	81.27	81.95	82.63	83.31	83.98
2.5	63.50	64.01	64.52	65.02	65.53	84.66	85.34	86.01	86.69	87.37
2.6	66.04	66.55	67.06	67.56	68.07	88.05	88.72	89.40	90.08	90.76
2.7	68.58	69.09	69.60	70.10	70.61	91.43	92.11	92.79	93.46	94.14
2.8	71.12	71.63	72.14	72.64	73.15	94.82	95.50	96.17	96.85	97.53
2.9	73.66	74.17	74.68	75.18	75.69	98.21	98.88	99.56	100.24	100.91
3.0	76.20	76.71	77.22	77.72	78.23	101.59	102.27	102.95	103.62	104.30
3.1	78.74	79.25	79.76	80.26	80.77	104.98	105.66	106.33	107.01	107.69

Temperature

The formulae for converting centigrade temperatures to Fahrenheit, and Fahrenheit to centigrade, are respectively:

$$°F. = \frac{9}{5}\ °C. + 32°$$

$$\text{and}\quad °C. = \frac{5}{9}\,(°F. - 32°)$$

Absolute zero = —273 °C.
= —459.4 °F.

0 °C. = 32 °F.
= 273 °A.

100 °C. = 212 °F.
= 373 °A.

TABLE 23. FAHRENHEIT INTO CENTIGRADE, AND CENTIGRADE INTO FAHRENHEIT

°F.	°C. 0	1	2	3	4	5	6	7	8	9
−70	−56.7	−57.2	−57.8	−58.3	−58.9	−59.4	−60.0	−60.6	−61.1	−61.7
−60	−51.1	−51.7	−52.2	−52.8	−53.3	−53.9	−54.4	−55.0	−55.6	−56.1
−50	−45.6	−46.1	−46.7	−47.2	−47.8	−48.3	−48.9	−49.4	−50.0	−50.6
−40	−40.0	−40.6	−41.1	−41.7	−42.2	−42.8	−43.3	−43.9	−44.4	−45.0
−30	−34.4	−35.0	−35.6	−36.1	−36.7	−37.2	−37.8	−38.3	−38.9	−39.4
−20	−28.9	−29.4	−30.0	−30.6	−31.1	−31.7	−32.2	−32.8	−33.3	−33.9
−10	−23.3	−23.9	−24.4	−25.0	−25.6	−26.1	−26.7	−27.2	−27.8	−28.3
− 0	−17.8	−18.3	−18.9	−19.4	−20.0	−20.6	−21.1	−21.7	−22.2	−22.8
+ 0	−17.8	−17.2	−16.7	−16.1	−15.6	−15.0	−14.4	−13.9	−13.3	−12.8
10	−12.2	−11.7	−11.1	−10.6	−10.0	− 9.4	− 8.9	− 8.3	− 7.8	− 7.2
20	− 6.7	− 6.1	− 5.6	− 5.0	− 4.4	− 3.9	− 3.3	− 2.8	− 2.2	− 1.7
30	− 1.1	− 0.6	0.0	+ 0.6	1.1	1.7	2.2	2.8	3.3	3.9
40	4.4	5.0	5.6	6.1	6.7	7.2	7.8	8.3	8.9	9.4
50	10.0	10.6	11.1	11.7	12.2	12.8	13.3	13.9	14.4	15.0
60	15.6	16.1	16.7	17.2	17.8	18.3	18.9	19.4	20.0	20.6
70	21.1	21.7	22.2	22.8	23.3	23.9	24.4	25.0	25.6	26.1
80	26.7	27.2	27.8	28.3	28.9	29.4	30.0	30.6	31.1	31.7
90	32.2	32.8	33.3	33.9	34.4	35.0	35.6	36.1	36.7	37.2
100	37.8	38.3	38.9	39.4	40.0	40.6	41.1	41.7	42.2	42.8

°C.	°F. 0	1	2	3	4	5	6	7	8	9
−50	−58.0	−59.8	−61.6	−63.4	−65.2	−67.0	−68.8	−70.6	−72.4	−74.2
−40	−40.0	−41.8	−43.6	−45.4	−47.2	−49.0	−50.8	−52.6	−54.4	−56.2
−30	−22.0	−23.8	−25.6	−27.4	−29.2	−31.0	−32.8	−34.6	−36.4	−38.2
−20	− 4.0	− 5.8	−7.6	−9.4	−11.2	−13.0	−14.8	−16.6	−18.4	−20.2
−10	14.0	12.2	10.4	8.6	6.8	5.0	3.2	+ 1.4	− 0.4	− 2.2
− 0	32.0	30.2	28.4	26.6	24.8	23.0	21.2	19.4	17.6	15.8
+ 0	32.0	33.8	35.6	37.4	39.2	41.0	42.8	44.6	46.4	48.2
10	50.0	51.8	53.6	55.4	57.2	59.0	60.8	62.6	64.4	66.2
20	68.0	69.8	71.6	73.4	75.2	77.0	78.8	80.6	82.4	84.2
30	86.0	87.8	89.6	91.4	93.2	95.0	96.8	98.6	100.4	102.2
40	104.0	105.8	107.6	109.4	111.2	113.0	114.8	116.6	118.4	120.2

Wind Velocity

1 mile per hour = 0.44704 meter per second
= 1.46667 feet per second
= 1.6093 kilometers per hour

1 meter per second = 2.2369 miles per hour
= 3.2808 feet per second
= 3.6 kilometers per hour

1 foot per second = 0.68182 mile per hour
= 0.30480 meter per second
= 1.09729 kilometers per hour

1 kilometer per hour = 0.62137 mile per hour
= 0.27778 meter per second
= 0.91134 foot per second

TABLE 24. MILES PER HOUR INTO METERS PER SECOND, FEET PER SECOND, AND KILOMETERS PER HOUR

m.p.h.	m.p.s.	ft./sec.	km./hr.	m.p.h.	m.p.s.	ft./sec.	km./h
1	0.4	1.5	1.6	51	22.8	74.8	82.1
2	0.9	2.9	3.2	52	23.2	76.3	83.7
3	1.3	4.4	4.8	53	23.7	77.7	85.3
4	1.8	5.9	6.4	54	24.1	79.2	86.9
5	2.2	7.3	8.0	55	24.6	80.7	88.5
6	2.7	8.8	9.7	56	25.0	82.1	90.1
7	3.1	10.3	11.3	57	25.5	83.6	91.7
8	3.6	11.7	12.9	58	25.9	85.1	93.3
9	4.0	13.2	14.5	59	26.4	86.5	95.0
10	4.5	14.7	16.1	60	26.8	88.0	96.6
11	4.9	16.1	17.7	61	27.3	89.5	98.2
12	5.4	17.6	19.3	62	27.7	90.9	99.8
13	5.8	19.1	20.9	63	28.2	92.4	101.4
14	6.3	20.5	22.5	64	28.6	93.9	103.0
15	6.7	22.0	24.1	65	29.1	95.3	104.6
16	7.2	23.5	25.7	66	29.5	96.8	106.2
17	7.6	24.9	27.4	67	30.0	98.3	107.8
18	8.0	26.4	29.0	68	30.4	99.7	109.4
19	8.5	27.9	30.6	69	30.8	101.2	111.0
20	8.9	29.3	32.2	70	31.3	102.7	112.7
21	9.4	30.8	33.8	71	31.7	104.1	114.3
22	9.8	32.3	35.4	72	32.2	105.6	115.9
23	10.3	33.7	37.0	73	32.6	107.1	117.5
24	10.7	35.2	38.6	74	33.1	108.5	119.1
25	11.2	36.7	40.2	75	33.5	110.0	120.7
26	11.6	38.1	41.8	76	34.0	111.5	122.3
27	12.1	39.6	43.5	77	34.4	112.9	123.9
28	12.5	41.1	45.1	78	34.9	114.4	125.5
29	13.0	42.5	46.7	79	35.3	115.9	127.1
30	13.4	44.0	48.3	80	35.8	117.3	128.7
31	13.9	45.5	49.9	81	36.2	118.8	130.4
32	14.3	46.9	51.5	82	36.7	120.3	132.0
33	14.8	48.4	53.1	83	37.1	121.7	133.6
34	15.2	49.9	54.7	84	37.6	123.2	135.2
35	15.6	51.3	56.3	85	38.0	124.7	136.8
36	16.1	52.8	57.9	86	38.4	126.1	138.4
37	16.5	54.3	59.5	87	38.9	127.6	140.0
38	17.0	55.7	61.2	88	39.3	129.1	141.6
39	17.4	57.2	62.8	89	39.8	130.5	143.2
40	17.9	58.7	64.4	90	40.2	132.0	144.8
41	18.3	60.1	66.0	91	40.7	133.5	146.4
42	18.8	61.6	67.6	92	41.1	134.9	148.1
43	19.2	63.1	69.2	93	41.6	136.4	149.7
44	19.7	64.5	70.8	94	42.0	137.9	151.3
45	20.1	66.0	72.4	95	42.5	139.3	152.9
46	20.6	67.5	74.0	96	42.9	140.8	154.5
47	21.0	68.9	75.6	97	43.4	142.3	156.1
48	21.5	70.4	77.2	98	43.8	143.7	157.7
49	21.9	71.9	78.9	99	44.3	145.2	159.3
50	22.4	73.3	80.5	100	44.7	146.7	160.9

Wind Pressure[1]

$$P = 0.004\ V^2$$

in which

P = pressure plus suction per square foot of flat surface normal to the wind,

and V = actual (not average) wind speed in miles per hour.

Miscellaneous Conversion Factors

1 foot	=0.3048 meter
1 meter	=39.37 inches
	=3.2808 feet
1 mile	=1.6093 kilometers
1 kilometer	=0.62137 mile
1 statute mile	=0.8684 nautical mile
1 nautical mile	=6,080.2 feet
	=1.1516 statute miles
1 grain	=0.06480 gram
1 gram	=15.432 grains
1 pound	=0.45359 kilogram
1 kilogram	=2.2046 pounds
1 cubic foot	=0.02832 cubic meter
1 cubic meter	=35.314 cubic feet

1 pound per cubic foot	=16.018 kilograms per cubic meter
1 kilogram per cubic meter	=0.06243 pound per cubic foot
1 grain per cubic foot	=2.2883 grams per cubic meter
1 gram per cubic meter	=0.4370 grain per cubic foot
1 pound per square inch	=70.307 grams per square centimeter
1 gram per square centimeter	=0.01422 pound per square inch
1 pound per square foot	=4.8824 kilograms per square meter
1 kilogram per square meter	=0.00142 pound per square inch
	=0.2048 pound per square foot

[1]Hugh L. Dryden and George C. Hill, "Wind Pressures on Structures," Bureau of Standards Scientific Paper 523, 1926.

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